Augmented Reality in Education 2023: innovations, applications, and future directions

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Abstract
The 6th International Workshop on Augmented Reality in Education (AREdu 2023) brought together researchers and practitioners to explore the latest innovations and applications of AR technologies in educational contexts. This paper presents an overview of the workshop's proceedings, comprising 13 peer-reviewed papers spanning diverse areas. Key themes include the integration of AR with other emerging technologies like AI and VR, the design of immersive learning environments, and the evaluation of AR's impact on learning outcomes and motivation. Despite the challenges posed by the ongoing war in Ukraine, AREdu 2023's hybrid format enabled global participation and knowledge sharing. The papers collectively demonstrate AR's potential to transform education and provide valuable insights to guide future research and implementation efforts.

Keywords
augmented reality, educational technology, immersive learning, STEM education, teacher training, virtual environments, empirical studies

1. Introduction

Augmented **R**eality in **Edu**cation (AREdu) is a peer-reviewed international Computer Science workshop focusing on research advances and applications of virtual, augmented and mixed reality in education.

Figure 1: AREdu 2023 logo.

The 6th International Workshop on Augmented Reality in Education (AREdu 2023), held on May 17, 2023, in Kryvyi Rih, Ukraine, provided a dynamic platform for researchers, educators, and technology developers to share their latest findings and experiences in the rapidly evolving field of AR in education. Building on the success of previous editions [1, 2, 3, 4, 5, 6], AREdu 2023 attracted a diverse array of contributions exploring the design, implementation, and evaluation of AR-based learning environments across various educational levels and subject areas.

AREdu topics of interest since 2018:

- Virtualization of learning: principles, technologies, tools
- Augmented reality gamification
- Design and implementation of augmented reality learning environments
- Augmented reality in science education
- Augmented reality in professional training and retraining

This volume represents the proceedings of the AREdu 2023. It comprises 13 contributed papers that were carefully peer-reviewed and selected from 17 submissions. At least three program committee members reviewed each submission.

AREdu 2023: 6th International Workshop on Augmented Reality in Education, May 17, 2023, Kryvyi Rih, Ukraine
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The workshop's proceedings showcase the breadth and depth of current research on educational AR. From theoretical frameworks to empirical studies and practical applications, the papers collectively demonstrate AR's immense potential to enhance learning experiences, foster engagement and motivation, and develop critical 21st-century skills.

2. AREdu 2023 committees

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3. Proceedings overview

3.1. Virtualization of learning: principles, technologies, tools

The paper "Using native virtualization technologies for teaching IP telephony to future IT specialists" by Pavlenko and Pavlenko [44] explores the application of virtualization technologies for teaching IP telephony to future IT specialists. The effective training of these students requires the development of competencies in installing, operating and maintaining various operating systems and IP telephony software in both local and global network environments. One potential solution to address the challenges of providing such training is the introduction of virtualization technology in the educational process.

The paper reviews different types of virtualization approaches, including full emulation, paravirtualization, native virtualization, operating system-level virtualization, and application-level virtualization. It concludes that native virtualization is the most suitable for creating a virtual training laboratory for IP telephony, as it allows running multiple guest operating systems designed for the same architecture as the host, simulating a computer network with IP telephony servers and clients on a single personal computer.

The study then compares three popular native virtualization solutions—VMware Workstation, Parallels Workstation, and VirtualBox—in terms of their features, supported operating systems, network adapters, licensing costs, etc. Based on this analysis, VirtualBox is identified as the optimal tool for developing a network lab for training future IT professionals in IP telephony, given its support for multiple operating systems, ability to connect up to 36 network adapters to a virtual machine, and free distribution.

Using VirtualBox, a repository of virtual machines was created to support a series of laboratory works on topics such as installing Asterisk and Free PBX, configuring IP telephony servers, setting up dial plans, managing calls, integrating voice services and menus, etc. The virtual laboratory includes server hosts running Ubuntu and Asterisk Free PBX and client hosts running Windows and Linux with IP telephony software like Linphone Desktop (figure 2). This setup enables students to simulate the interaction of server hosts on the Internet and test IP telephony features on user devices.

To evaluate the effectiveness of the proposed virtualization-based training approach, a pedagogical

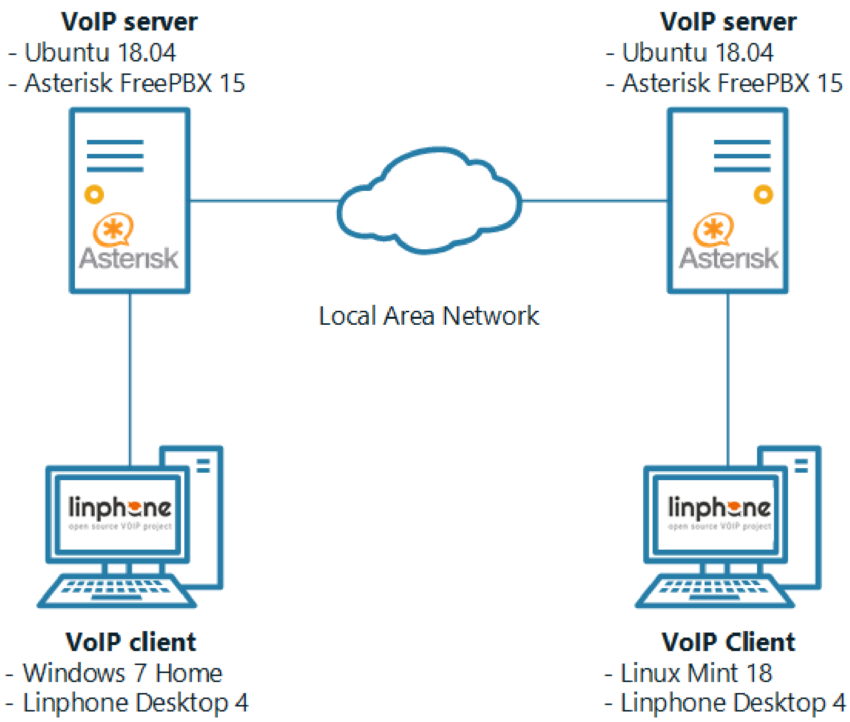

Figure 2: Virtual laboratory of IP telephony [44].

experiment was conducted involving control and experimental groups of students from Berdyansk State Pedagogical University. The experimental group used the VirtualBox-based virtual laboratory, while the control group used a traditional hardware network laboratory.

The results showed positive dynamics in the levels of knowledge acquisition and skill development in both groups, but the improvement was more pronounced in the experimental group. The share of students who completed 75-90% of the tasks increased by 14% (vs 5% in the control), and those completing more than 50% of advanced tasks increased by 40% (vs no change in the control). Statistical tests confirmed significant differences in the learning outcomes of the two groups after the experiment.

The research "Integration of laboratory equipment in remote learning environments" by Vasylieva et al. [45] examines the integration and implementation strategies for laboratory work within remote learning environments, alongside an analysis of virtual laboratories as an alternative to traditional practical training. The study is motivated by the unprecedented challenges faced by higher education institutions in conducting laboratory instruction during the COVID-19 pandemic and the ongoing Russian invasion of Ukraine. These crises have catalyzed a rapid transition from physical to virtual learning spaces, necessitating innovative solutions for practical skill development, particularly in technical disciplines.

The paper begins by reviewing the global impact of the pandemic on education, highlighting the mass disruption of learning activities and the digital divide in access to personal computers and internet connectivity. It then discusses the expansion of web-based distance education in higher education and the need for constant improvement in technological and methodological support. Research on the effectiveness, advantages, and barriers of online learning is emphasized, alongside the importance of engaging students in the virtual environment.

The integration of laboratory work in remote settings is identified as a critical challenge, especially for STEM fields that require interaction with physical equipment. Remote and virtual laboratories are proposed as potential solutions, with the former involving real equipment controlled via software and hardware interfaces and the latter emulating experiments through mathematical models.

The case study focuses on the laboratories of bioelectronics and biomechanics at the Department of Computer Information Technologies, Donbas State Engineering Academy. These labs are equipped with modern computer numerical control (CNC) machines and 3D printers, which allow students to translate computer models into physical objects. The CNC machines include the Krechet-4060 for 2D/3D milling and the Sherline 5410 and 4410 for drilling, milling, and turning. The FARM2 3D printer is used for additive manufacturing with various plastics.

While full automation of these machines for remote operation is currently infeasible due to the need for human intervention in specific tasks (e.g., tool/material changeout), the paper explores possibilities for remote monitoring and control. Existing solutions using open-source firmware, single-board computers, and client-server architectures are reviewed. For example, the RepRap system enables web-based control of 3D printers, with potential enhancements through sensor integration and machine learning for quality monitoring.

The universal testing machine UIT STM 001 is also considered for remote laboratory work on the mechanical properties of materials. In addition to partial remote access, virtual laboratory simulations are proposed as an alternative approach. A prototype virtual lab for a "Resistance of Materials" course is described (figure 3), which replicates the entire experimental cycle from sample preparation to data analysis.

The study "Developing pre-service teachers' digital competence through informatics disciplines in teacher education programs" by Moiseienko et al. [46] investigated the effectiveness of the proposed didactic conditions and structural-functional model for developing pre-service teachers' digital competence through informatics disciplines in teacher education programs. The rapid digitalization of society and education has highlighted the need for educators to possess a high level of digital competence to integrate digital technologies into their professional practice effectively. However, studies have revealed that pre-service teachers often lack sufficient digital competence, suggesting that existing informatics courses do not adequately contribute to the full and targeted development of this competence.

To address this issue, a structural-functional model was developed, incorporating three specific

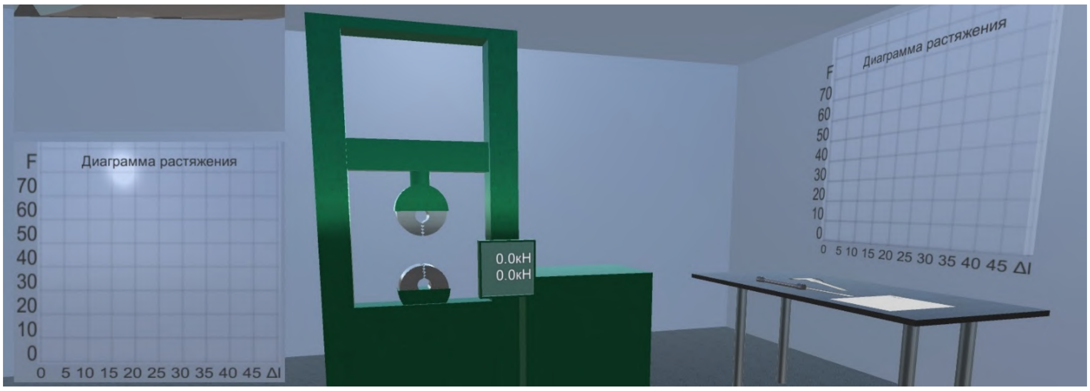

Figure 3: Program interface with three-dimensional models, interface, and mini cameras for simultaneous control of all processes [45].

didactic conditions:

1. Motivational conditionality of subjects' interaction in the digital learning environment.
2. Structuring of educational information in problematic, heuristic and integrative learning models and its translation into project activities.
3. Ensuring a systematic, complicated nature of students' learning activities with diagnostics and timely correction of outcomes using modern ICT.

A pedagogical experiment was conducted to test the effectiveness of the proposed didactic conditions and model. The study followed a quasi-experimental design with a control group ($n = 93$) and an experimental group ($n = 95$) of pre-service teachers from two Ukrainian pedagogical universities over four academic years. The control group studied according to traditional informatics discipline programs, while the experimental group followed an experimental program implementing the proposed didactic conditions and model.

Digital competence formation was assessed according to four structural-criterial components (motivational-value, cognitive-informational, operational-activity, and personal-reflexive) using a range of diagnostic methods, including tests, questionnaires, interviews, practical tasks, competency matrices, expert evaluations, case studies, educational projects, and reflective blogs.

The experimental group demonstrated positive, statistically significant dynamics in the levels of digital competence formation compared to the control group, with the greatest development observed in the cognitive-informational (+35.79%) and motivational-value (+25.26%) components. Paired-sample t-tests revealed significant improvements in the experimental group's digital competence scores across all four components, while independent-sample t-tests showed significantly higher post-experiment scores for the experimental group compared to the control group.

Qualitative findings from thematic analysis of interviews, case studies, educational projects, and blog entries revealed several key themes related to the development of digital competence in the experimental group, including enhanced motivation and engagement, improved understanding of digital technologies, increased confidence in using digital tools, collaborative learning and peer support, and reflective practice and self-awareness.

The results confirm the effectiveness of the proposed didactic conditions and structural-functional model for developing pre-service teachers' digital competence through informatics disciplines. The findings underscore the importance of adopting a holistic, integrated approach to informatics disciplines, combining technical skills, pedagogical knowledge, and practical application through authentic, project-based learning experiences.

The study has implications for teacher education policy and practice. It suggests the need to prioritize the intentional and systematic development of pre-service teachers' digital competence, adopt evidence-based strategies, and invest in necessary infrastructure, resources, and support systems. Future research could explore the long-term impact of digital competence development interventions and adapt the proposed model for different contexts and specializations within teacher education.

The adoption of the new Law of Ukraine "On Education" in 2017 granted greater autonomy to schools in academic, organizational, financial and personnel matters. This shift requires new approaches to train school principals and directors in strategic management skills. The paper "Implementing business simulation games for strategic management training of educational leaders in Ukraine" by Pazdrii and Kuprievych [47] explores the use of business simulation games as an innovative tool to develop the economic and managerial competencies needed by educational leaders to navigate these reforms.

The authors conducted a case study of training held in Ukraine from 2016 to 2021 that utilized business simulations. Over 1,200 participants from preschool, secondary, vocational and higher education institutions were surveyed regarding their perceptions and learning outcomes. The results highlighted a gap between how schools and private businesses perceive key concepts like customers, products and resources. Over 50% of directors agreed schools are economic entities, 87% saw students as the "raw material", and clients were identified as parents, the state, universities and sometimes businesses. However, some directors rejected applying classical management principles to schools.

The paper identifies several objective reasons for this disconnect, including the legacy of the industrial economy, the absolutism of the socialist system, and low human value in the USSR. Subjective factors were also noted, such as unwillingness to change, lack of tools to transition from public administration to autonomy, legislative uncertainty, and a lack of mutual understanding between the educational and business communities.

To overcome these challenges, the authors propose a systemic approach to economic management training that engages all levels – customers (students), teachers, deputy principals and principals. For leaders, it recommends viewing schools as non-profit economic organizations optimizing limited resources. Deputies are encouraged to expand their roles to encompass marketing, finance and HR. External stakeholder engagement with other schools, clients, businesses and authorities is also emphasized as crucial.

The paper reviews different training technologies and concludes that business games and simulations are the most accessible and impactful for quickly developing practical skills. Gamification and virtual reality, while promising, are seen as too resource-intensive and immersive for time-constrained principals. The authors share best practices and lessons learned from delivering over 120 simulation-based trainings to 600+ educational leaders from 2015-2020. Key success factors included setting expectations to challenge traditional thinking, explaining economic terminology, updating digital skills, providing guidance on interpreting results, and linking the simulation to real-world education sector reforms.

The adoption of digital technologies in education has accelerated rapidly in recent times, driven by technological progress and catalyzed by the global COVID-19 pandemic. The article "The educational technology landscape in Ukraine" by Nehrey and Zomchak [48] analyzes the present landscape and prospects for Educational Technology (EdTech) in Ukraine.

Efficiency analyses using the Data Envelopment Analysis (DEA) methodology were performed to assess the effectiveness of education expenditures in Europe and Central Asia. The results revealed substantial opportunities for Ukraine to enhance educational outcomes via increased investment and technology integration. While European countries generally demonstrated effective education spending, Ukraine and other former Soviet countries exhibited extremely inefficient expenditures. A second DEA model evaluating the efficiency of education in producing an advanced labour force showed that countries with lower spending on education, like Ukraine, achieved higher efficiency than those with significant expenditures, like Germany. These findings suggest great potential for productivity gains through EdTech innovations in Ukraine.

Globally, venture capital funding for EdTech reached a peak during the pandemic but has since declined to pre-2017 levels. China has been the top investor over the past decade, with the US and Europe trailing significantly behind. The Ukrainian EdTech startup ecosystem has expanded to over 80 companies, with 11 projects recognized among the top 200 in Europe by HolonIQ. These startups deliver solutions spanning tutoring (Preply), language instruction (EnglishDom), MOOCs (Prometheus), K-12 education (EdPro), information platforms (Osvitoria), learning management systems (Na Urok, eTutorium), IT education (Mate academy), and writing tools (Grammarly).

A comparative analysis of prominent Ukrainian EdTech projects highlighted their strengths, such as reaching large audiences, leveraging innovative technologies, and offering practical solutions. However, challenges were also identified, including limited mobile applications, high product costs, lack of offline support, and strong competition.

A SWOT analysis of Ukraine's EdTech ecosystem revealed critical internal factors. Strengths included growing government and private sector demand for digital education and the potential for productivity gains. Weaknesses encompassed high technology costs, financing difficulties, bureaucratic hurdles, underdeveloped infrastructure, and lack of impact data. External opportunities were identified in the large student population, data-driven insights for educational improvement, and potential for workforce optimization. Threats included cybersecurity risks, inconsistent outcomes across contexts, and the potential for data access to exacerbate inequalities.

To fully realize the potential of EdTech in Ukraine, the authors recommend several strategic priorities:

1. Increase government spending on education and innovative technologies
2. Ensure access to financing for EdTech startups
3. Accelerate the digitalization of education through affordable ICT and e-government initiatives
4. Engage non-governmental organizations in promoting EdTech adoption
5. Create an enabling environment for the development of the EdTech ecosystem

Educational technology is a dynamic field with continuous developments and innovations shaping research directions and priorities. The Educational Technology Quarterly (ETQ) offers valuable insights into evolving trends within this domain through its broad publication of studies across various educational contexts and technologies. The paper "Shifting sands: analyzing trends in educational technology research published in Educational Technology Quarterly (2021-2023)" by Semerikov et al. [49] provides a bibliometric analysis of 72 research articles published in ETQ from 2021-2023 to identify key themes and changes in focus over this period.

The study utilized the VOSViewer software tool to conduct a bibliometric analysis of the abstract corpus. Author keywords were extracted, and maps of co-occurring keywords were generated and visualized (figure 4). Various bibliometric techniques were applied, including keyword analysis, temporal analysis, network analysis of co-occurrences, and geographic analysis of author locations.

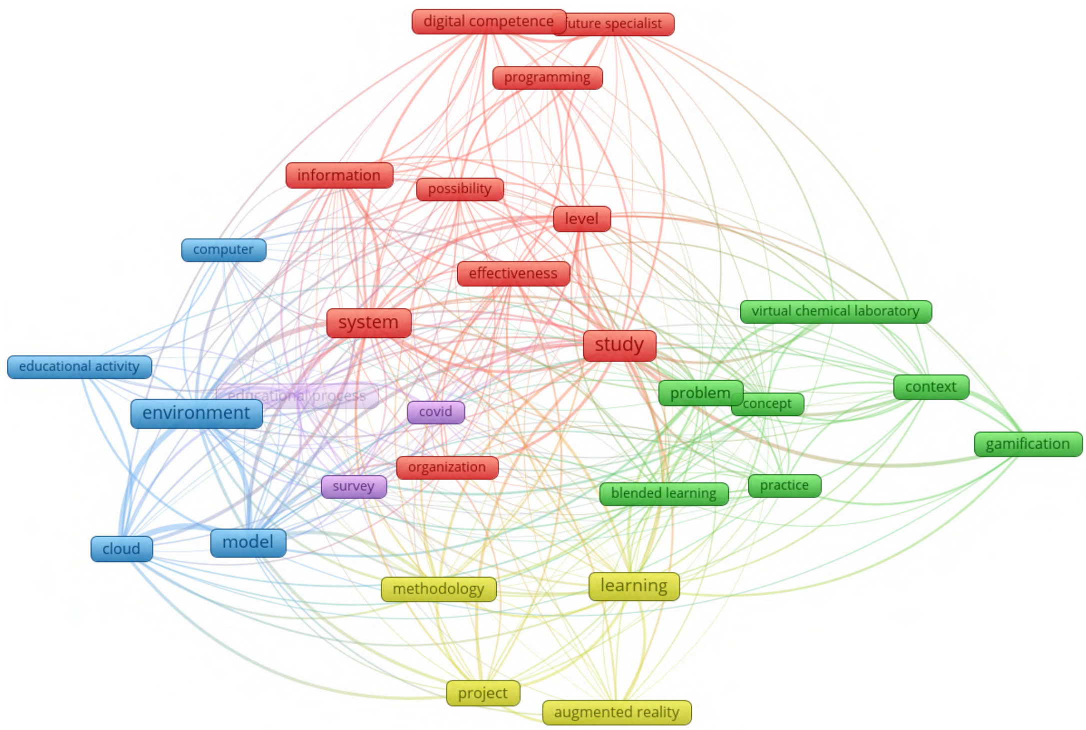

Figure 4: Co-occurrence network of keywords [49].

The keyword analysis revealed five distinct clusters of research topics:

1. Digital competence development and technology systems
2. Pedagogical models and educational concepts
3. Technological infrastructure and frameworks
4. Research methods and processes
5. COVID-19 pandemic-related research

Central keywords spanning multiple clusters, such as "learning", "level", "problem", and "effectiveness", indicated interdisciplinary topics connecting these research domains.

The temporal analysis mapped keywords by their publication dates, revealing patterns and changes in research focus over time. COVID-19-related terms emerged abruptly in 2021 and remained frequent, reflecting a surge in pandemic-driven research. "Cloud" gained traction in 2021, pointing to growing attention on cloud-based technologies and remote learning. Newer topics like "gamification" and "virtual chemical laboratory" gained prominence in 2022 and 2023. By 2023, keywords like "methodology", "problem", and "programming" overtook some earlier topics, indicating a return to more foundational research as the acute pandemic period receded. "Digital competence" displayed a rapidly growing, sustained interest since 2022.

The network analysis revealed strong linkages between keywords, such as "learning" and "level", and "cloud" and "environment." "Model" and "problem" formed connections across multiple clusters, suggesting their interdisciplinary nature. Peripheral keywords like "future specialist" and "virtual chemical laboratory" had fewer connections, pointing to their more domain-specific focus.

The geographic analysis of author affiliations highlighted the global distribution of research published in ETQ. While Ukraine dominated with 69% of publications, contributions from other countries, particularly Poland, the United States, and Israel, were notable. The proportion of contributions from Middle Eastern and African countries grew from 0% in 2021 to 25% in 2023, indicating increasing global diversification.

This bibliometric analysis provides quantitative evidence of recent trends and the evolving landscape of educational technology research in ETQ. The findings portray a field adapting to current shocks like the COVID-19 pandemic while expanding in scope and attention to longer-term priorities like enhancing digital skills. However, this study represents only a preliminary examination, and further work could conduct more sophisticated statistical analyses, contextualize the findings within broader technological and educational contexts, and compare ETQ's coverage with other journals in the field.

3.2. Augmented reality gamification

Gamification, the use of game design elements in non-game contexts, is a promising approach for enhancing motivation and engagement in software engineering education. However, its applications and effects are not yet well understood. The paper "A systematic review of gamification in software engineering education" by Korniienko et al. [50] aimed to synthesize the current state of evidence on the use and impacts of gamification in software engineering education.

The review followed the PRISMA 2020 guidelines (figure 5). Scopus searched for peer-reviewed papers published up to March 1, 2023, that described empirical studies of gamification in software engineering courses and measured impacts on learning outcomes and/or student perceptions. Study characteristics, gamification approaches, software engineering topics, research methods, and key findings were extracted. The risk of bias was assessed using an adapted ROBINS-I tool. Quantitative and qualitative results were synthesized narratively, and the certainty of evidence was evaluated using the GRADE approach.

Twenty-nine studies met the inclusion criteria. The studies most commonly employed points (17 studies), challenges (14 studies), leaderboards (11 studies), and badges (9 studies) to gamify the learning of software process (12 studies), software design (9 studies), and software professional practices (7 studies). The majority of studies (21) reported positive impacts on student engagement, motivation, and/or performance, but the lack of validated measurement instruments and controlled study designs

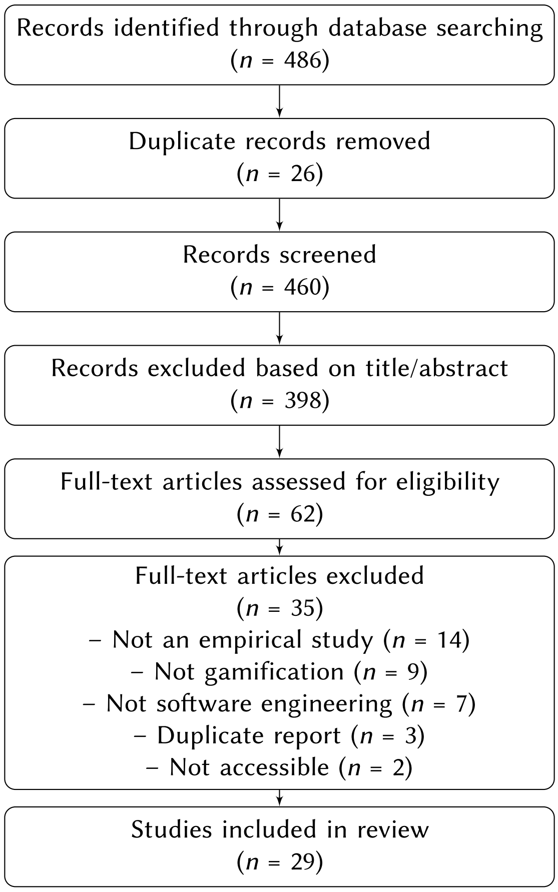

Figure 5: PRISMA flow diagram of the study selection process [50].

limited the quality of evidence. Most studies (18/29) had a serious overall risk of bias, primarily due to confounding and selection bias. The certainty of evidence was rated as low or very low for all outcomes.

The review found that a variety of gamification strategies have been applied in software engineering education, primarily in university courses. The impacts on learning outcomes were generally positive but small and inconsistent across studies. The effects on student engagement and motivation were more consistently positive, but the evidence was of very low certainty. User experiences and acceptance of gamified learning activities were mostly positive but with low certainty evidence. The heterogeneity in gamification designs, software engineering topics, and educational contexts, as well as the methodological limitations of the primary studies, precluded robust quantitative synthesis and definitive conclusions about the effectiveness of gamification.

Gamification appears to be a promising approach for enhancing software engineering education, but more rigorous, theory-driven research is needed to identify effective strategies for specific learning objectives and contexts. Educators and researchers should carefully consider how specific gamification elements align with target competencies and pedagogical principles, balance extrinsic rewards and intrinsic motivation, engage students as co-designers, and plan for the resources and support needed for successful implementation.

This systematic review found that gamification is an increasingly popular but under-researched approach in software engineering education. While the evidence suggests some positive impacts, particularly on student engagement and motivation, the certainty of the evidence is low. Future research should employ rigorous, controlled designs and validated measures to evaluate the effectiveness of specific gamification strategies for targeted software engineering learning outcomes. Attention to implementation fidelity and the resources needed to overcome potential barriers will also be critical for realizing the potential of gamification to transform software engineering education.

The study "Gamification in higher education: methodology" by Yechkalo et al. [51] examines the implementation of gamification in higher education, focusing on its effectiveness and pedagogical conditions. Gamification, the application of game-design elements and principles in non-game contexts, has emerged as a promising approach to enhance student engagement and learning outcomes. However, its successful integration into higher education requires careful consideration of pedagogical conditions and a systematic methodology.

The research presents a structural-functional model for gamification in higher education, comprising five key blocks: objective, content, methodological-organizational, diagnostic, and resultant (figure 6). The objective block defines the purpose and objectives of the educational process, while the content block includes the pedagogical conditions for effective gamification use. The methodological-organizational block outlines the technology for implementing gamification, and the diagnostic block specifies criteria and levels for evaluating its effectiveness. Finally, the resultant block establishes the desired outcome of the model's implementation.

Two key pedagogical conditions are proposed to increase the effectiveness of gamification in higher education significantly:

1. Developing positive motivation for using gamification by engaging students in quasi-professional activities that simulate real-world problem situations.
2. Strengthening the practical orientation of the educational process based on the principles of variability and combining traditional and innovative methods, forms, and activities.

These conditions aim to enhance student motivation, bridge the gap between theory and practice, and promote the development of relevant professional skills.

To validate the proposed methodology and pedagogical conditions, a pedagogical experiment was conducted involving control and experimental groups of students. The effectiveness of gamification was evaluated using three criteria: motivational, cognitive, and operational, each with four levels: high, sufficient, medium, and low. These criteria were assessed using various indicators, such as students' interest and participation in learning activities, completeness and systematicity of knowledge, and ability to apply skills in professional contexts.

The results of the formative stage of the experiment showed significant improvements in the experimental group across all three criteria. The proportion of students demonstrating high levels of gamification effectiveness increased, while those at medium and low levels decreased. These changes were more pronounced in the experimental group compared to the control group, highlighting the impact of the implemented methodology and pedagogical conditions.

3.3. Design and implementation of augmented reality learning environments

The paper "Designing an immersive cloud-based educational environment for universities: a comprehensive approach" by Semerikov et al. [52] presents a comprehensive approach to designing an immersive cloud-based educational environment (ICBEE) for universities. As digital transformation advances in higher education, there is a growing need for innovative learning environments that leverage cutting-edge technologies to enhance the quality and accessibility of educational services. Immersive learning approaches based on augmented reality (AR) and virtual reality (VR), combined with the power and flexibility of cloud computing, offer new opportunities for creating interactive, engaging, and practice-oriented educational experiences.

The paper defines an ICBEE as an integrated system that combines AR/VR tools, cloud services, learning management platforms, and various educational resources and activities to support learning, research, and management processes in a university setting. The design and implementation of such environments require a solid scientific and methodological foundation that considers the complex interplay of technological, pedagogical, and organizational factors.

The paper identifies the main structural components of ICBEE as spatial-semantic, technological, content, communication, and immersive. These components form an integrated system in which physical and digital spaces are blended, cloud-based tools and platforms mediate the learning process, and immersive technologies add an extra layer of interactivity and engagement.

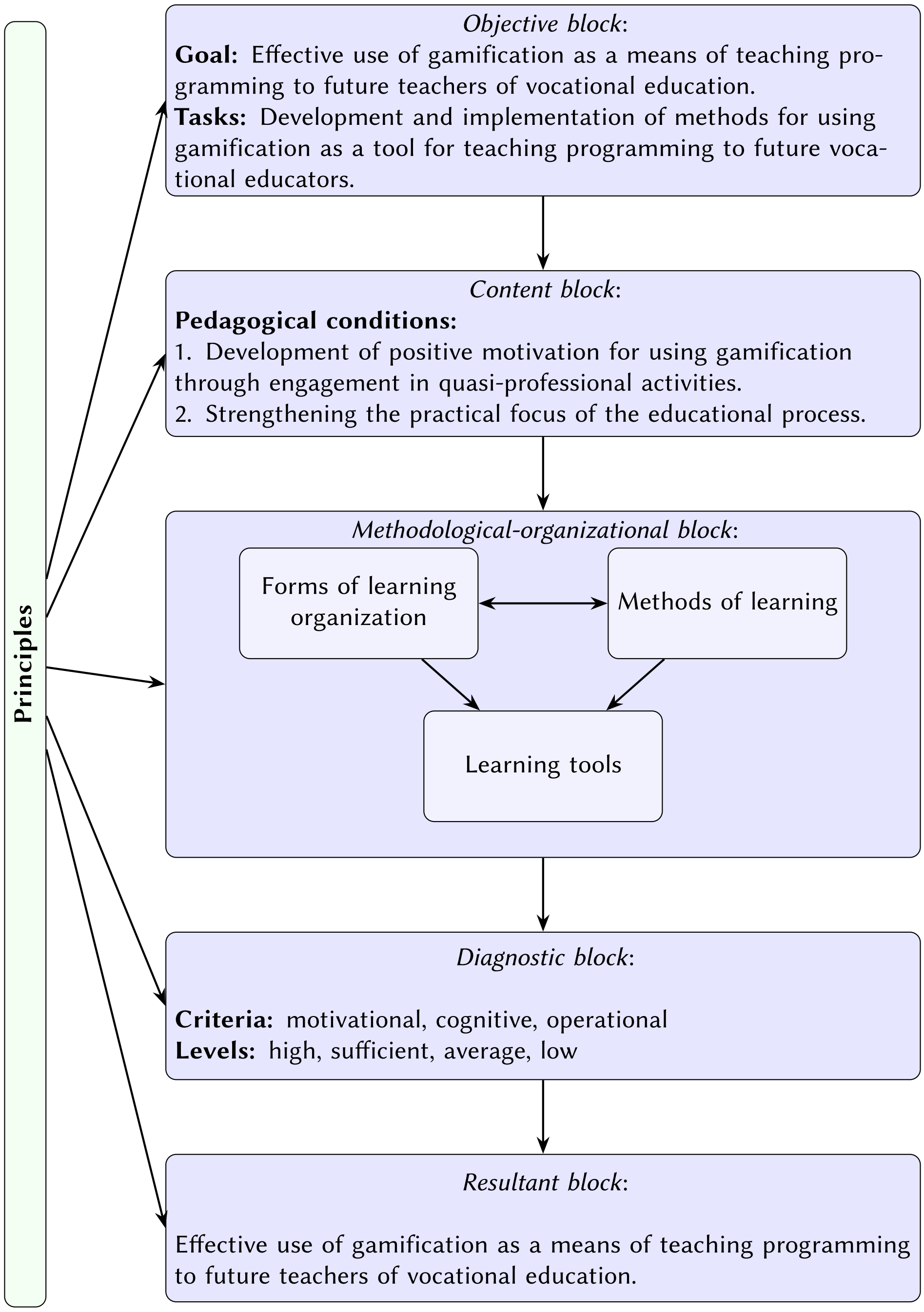

Figure 6: Structural-functional model for gamification in higher education [51].

The functional modules and services of ICBEE include a learning management module, immersive learning content authoring and delivery module, institutional repository module, learning analytics and reporting module, communication and collaboration services, and IT infrastructure management and security services. The integration and interoperability of these modules and services are essential for creating a seamless and effective educational experience.

The paper also discusses the principles of designing immersive learning experiences, such as interactivity and engagement, realism and authenticity, adaptability and personalization, multimodality and multisensory feedback, collaborative and social learning, and safety and ethics. Guidelines for developing educational AR applications and approaches to designing VR simulations and training systems are provided, along with specific examples.

The proposed general metamodel of ICBEE captures its essential elements and their relationships, consisting of four main layers: infrastructure, platforms and services, educational content and applications, and learning and research activities (figure 7). The metamodel highlights the cross-cutting aspects of ICBEE, such as the development of learners' digital competencies and the integration and interoperability of different components and services.

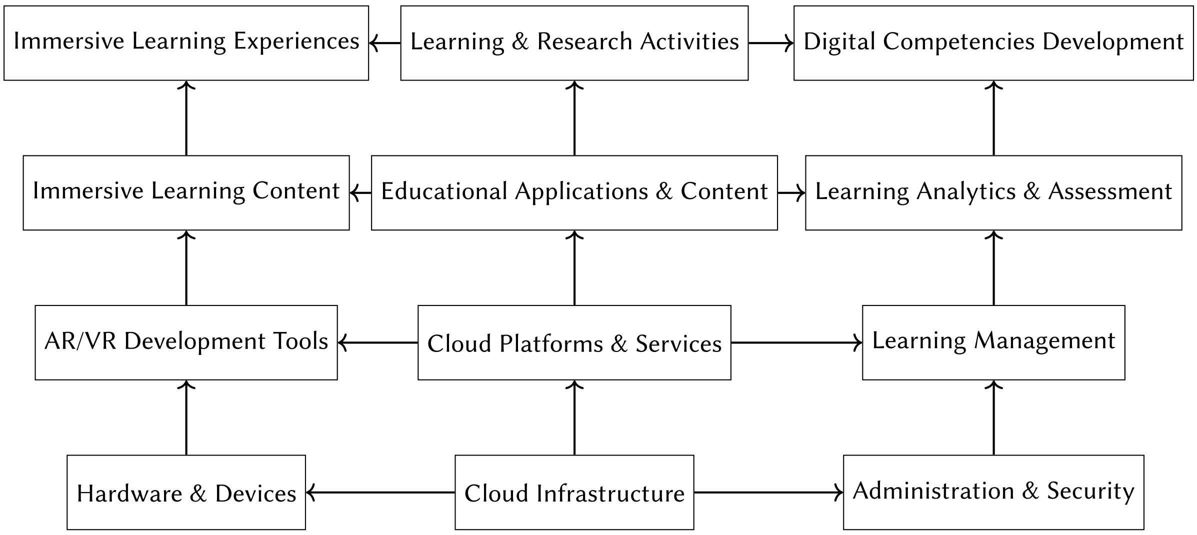

Figure 7: General metamodel of ICBEE [52].

3.4. Augmented reality in science education

The article "Enhancing mathematics education with GeoGebra and augmented reality" by Kramarenko et al. [53] explores the potential of integrating GeoGebra software with augmented reality technology to enhance mathematics education. GeoGebra, a powerful dynamic mathematics software, allows for the interactive exploration of mathematical concepts through dynamic visualizations. Its recent venture into AR, with GeoGebra AR applications, presents exciting opportunities for engaging students with mathematical ideas in innovative ways.

The article examines current research on GeoGebra AR in mathematics education and provides examples of its applications across various mathematical domains and educational levels. In secondary mathematics education, studies have shown that integrating GeoGebra AR improves students' spatial intelligence, academic performance, and problem-solving skills compared to traditional instruction. GeoGebra AR has been applied to topics such as geometry (visualizing 3D shapes, exploring cross-sections), algebra (graphing functions), and trigonometry (exploring graphs and transformations).

In higher education and STEAM (Science, Technology, Engineering, Arts, and Mathematics) contexts, GeoGebra AR has been used to enhance learning in calculus (visualizing 3D graphs and solids of revolution), engineering mathematics (spatial geometry), and interdisciplinary projects that connect mathematics with arts, culture, and history. These applications demonstrate the versatility of GeoGebra AR in promoting visualization, conceptual understanding, and authentic learning experiences.

The article also discusses the potential of AR technology to support and enhance key aspects of mathematical thinking. GeoGebra AR can serve as a tool to connect abstract mathematical knowledge to real-world situations, enable hypothesis testing and knowledge construction through the manipulation of AR models, and afford novel embodied interactions related to perspective, scale, and depth. However, more research is needed to unpack the cognitive processes involved and design AR-based tasks that optimize learning.

A case study on stereometry teaching is presented, showcasing tasks on combinations of polyhedra and solids of revolution, stereometric problems of applied content, and project work in GeoGebra 3D (figure 8). The case study highlights how AR can provide dynamic visualizations of 3D geometrical shapes, foster understanding of their relationships and construction methods, and enable intuitive hand gesture-based interactions. Project work, such as modelling playgrounds or artists' rooms, can integrate GeoGebra AR to develop students' STEM competencies, critical thinking, creativity, and collaboration skills.

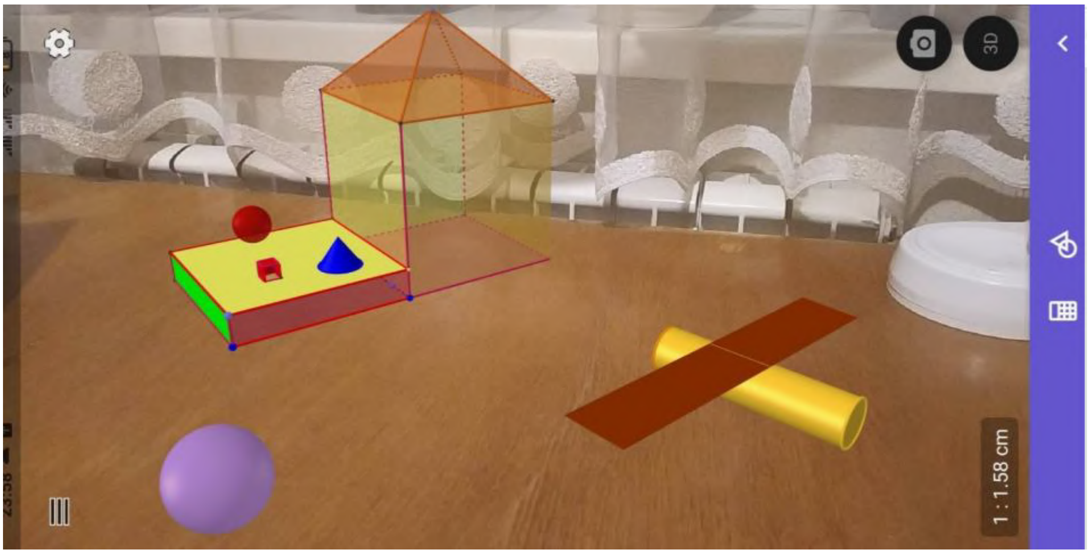

Figure 8: Sample implementation of the project "Playground" [53].

To effectively incorporate GeoGebra AR into mathematics curricula, the article recommends aligning AR activities with learning objectives, providing clear instructions and scaffolding, encouraging collaborative learning, assessing learning outcomes, and gathering feedback for iterative refinement. Professional development for teachers is crucial, as is attention to technological infrastructure and equity.

The increasing digitalization of education has highlighted the need for pre-service teachers in mathematics, physics and computer science to develop competencies in effectively utilizing information and communication technologies (ICT) in their teaching practice. Free and open-source software (FOSS) presents a valuable opportunity for educators to access powerful tools without the financial and legal barriers associated with proprietary software. The article "The utility of free software in the teaching of mathematics, physics and computer science for pre-service teachers" by Velychko and Fedorenko [54] examines the theoretical and methodological foundations for integrating FOSS into the professional training of pre-service teachers in these disciplines.

The study proposes a system for applying FOSS in teacher education, encompassing conceptual, content and technological components (figure 9). The conceptual subsystem outlines the goals, approaches, and principles of the system, with the primary objective of enhancing pre-service teachers' ICT competencies through FOSS. The content subsystem defines the structure of these competencies, emphasizing areas such as information and data literacy, digital content creation, and problem-solving. It also highlights the importance of open educational resources and e-learning. The technological subsystem focuses on the practical implementation, including stages of competency development, teaching methods, FOSS tools, and learning formats.

The effectiveness of the proposed system was evaluated through an experimental study involving 240 students from pedagogical universities in Ukraine. The results showed that the experimental group taught using the FOSS-based system, demonstrated significantly higher levels of ICT competency compared to the control group. In particular, they exhibited better skills in using FOSS tools for problem-solving, digital content creation and collaboration. The study also found a positive impact on student's motivation and confidence in their ability to integrate technology into their future teaching practice.

The paper discusses the benefits of FOSS in education, including cost savings, flexibility, skill development, and opportunities for collaboration. However, challenges such as lack of awareness, technical support, and training for educators have also been acknowledged. To address these, the authors propose

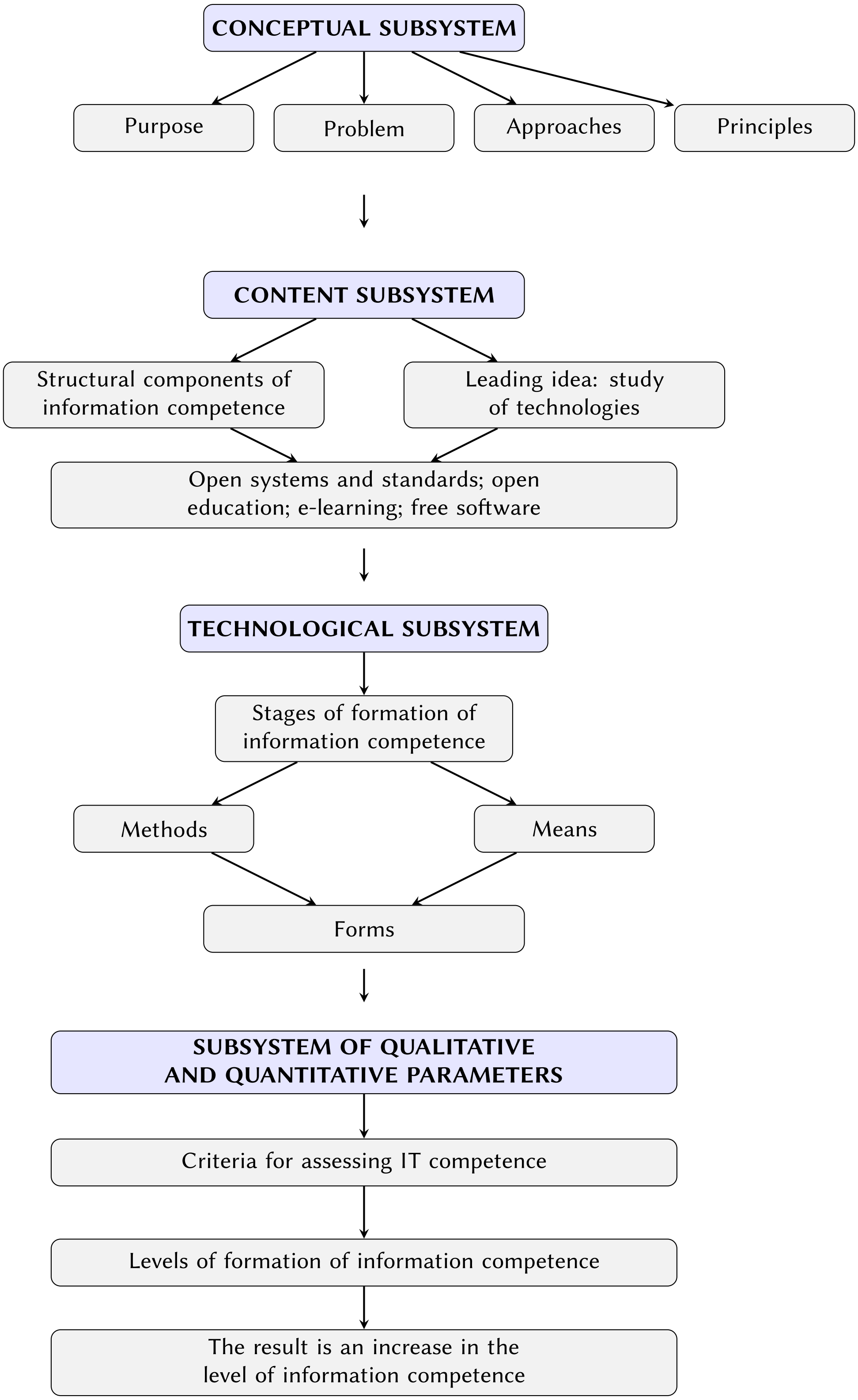

Figure 9: System for integrating free software into the professional training of pre-service teachers of mathematics, physics and computer science [54].

recommendations for integrating FOSS into teacher education programs:

1. Raise awareness about the benefits of FOSS among stakeholders
2. Provide training and support for educators to use FOSS tools effectively
3. Encourage collaboration and resource sharing within and across institutions

4. Integrate FOSS into the curriculum across disciplines
5. Foster partnerships with FOSS communities and industry

3.5. Augmented reality in professional training and retraining

Understanding the dynamics and outcomes of combat engagements is critical for analyzing military tactics, identifying best practices, and developing practical recommendations. However, open-source information on past battles is often incomplete, biased, or lacking the necessary detail for thorough analysis. Seeking to address this challenge, the paper "Interactive 3D visualizations for studying combat experiences and life cycles" by Barkatov et al. [55] proposes the use of interactive 3D visualizations in conjunction with the After Action Review (AAR) methodology and mathematical combat modelling to reconstruct and analyze combat experiences.

The key criterion for assessing the 3D visualizations is the degree of their adequacy to the actual combat episode in terms of stages, timeline, and elements. The visual information should approach reality maximally. Proposed criteria include information completeness and reliability, battle dynamics, effectiveness of combat actions, and accurate representation of terrain characteristics. NATO's AAR methodology, which focuses on establishing the facts, analyzing the causes and contributing factors, and deriving actionable lessons, is employed to structure the analysis.

Mathematical modelling of combat using Lanchester's equations complements the AAR by quantifying the dynamics and outcomes of engagements. By considering different initial force ratios, attrition rates, and engagement termination conditions, analysts can explore the sensitivity of outcomes to various factors and highlight the leverage points for achieving desired results.

The design of an effective combat visualization system follows principles of modularity, scalability, interoperability, user-centricity, and extensibility. The pipeline involves the formation, geometric processing, and rasterization of reliable data, while control programs handle initialization and interaction with the external environment (figure 10). Techniques such as discarding invisible terrain sections and reducing the utilization of distant areas help to optimize performance.

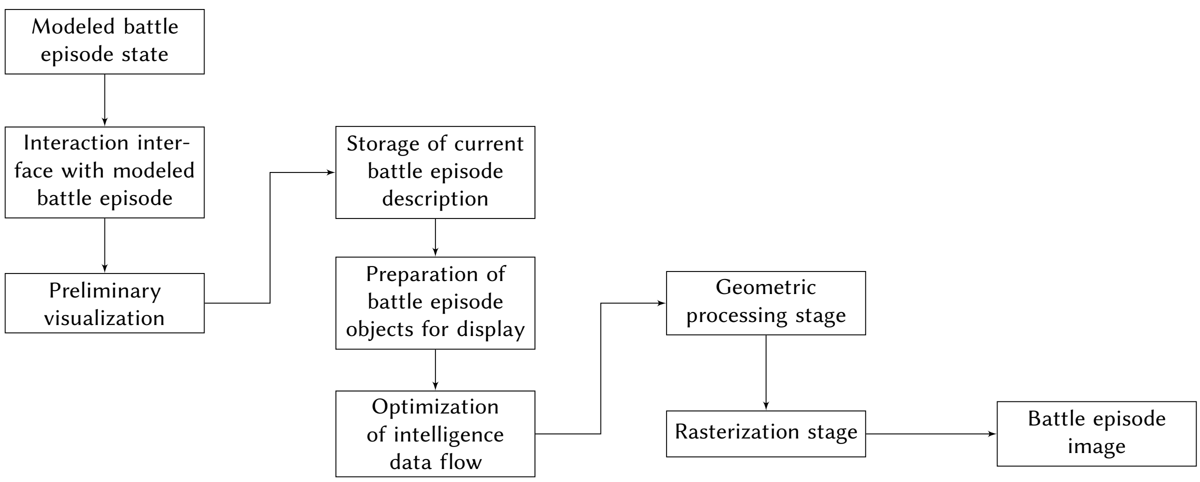

Figure 10: Battle episode visualization system [55].

The process of creating interactive 3D visualizations of combat episodes involves a systematic approach to data collection, terrain and entity modelling, animation, and interactive rendering. Key steps include:

1. Gathering and analyzing information from various sources to reconstruct the battle in sufficient detail.
2. Building a 3D model of the terrain using a digital elevation model and overlaying relevant features.
3. Placing 3D models of personnel, vehicles, and equipment according to their initial positions.
4. Animating the actions of each entity throughout the battle based on the collected data.

5. Integrating additional elements to enhance the immersion and information content of the visualization.
6. Rendering the complete visualization and packaging it for interactive display on various platforms.

The methodology is demonstrated through two case studies from the war in Eastern Ukraine: the defence of the "Seroga" strongpoint near Sanzharivka on January 28, 2015, and the assault on Logvinove on February 12, 2015. For each case, the 3D visualization was created using the Interactive 3D Visualization Constructor software, which allowed users to freely move the camera, pause and resume the playback, and toggle information overlays.

The AAR of these battles identified several key lessons, including the importance of well-prepared defensive positions, the decisive role of artillery and MLRS, the value of timely and organized withdrawals, and the criticality of situational awareness and rapid decision-making. These lessons were subsequently incorporated into training and doctrine for Ukrainian mechanized units.

Beyond AAR, the visualizations served as case studies for professional military education, exposing students to the complexity and chaos of modern combat. The realistic and immersive nature of the presentations also facilitated understanding and communication of the battles' significance when briefing senior leaders.

As the fidelity and sophistication of modelling and simulation technologies advance, the potential applications of interactive 3D visualization in the military domain will only expand. From mission planning and rehearsal to after-action review and training, immersive visualizations will play an increasingly central role in preparing the armed forces for the challenges of 21st-century warfare.

The rapid advancement of digital technologies is transforming educational practices across all sectors, with immersive technologies like virtual reality at the forefront of this revolution. In vocational higher education, there is growing interest in using VR to enhance students' professional training. VR offers unique affordances for creating realistic simulations of workplace environments, allowing students to practice skills in safe, controlled settings and providing experiences that would be difficult or impossible to replicate in traditional educational contexts.

The paper "Methodical foundations and implementation strategies for virtual reality in professional training of vocational higher education students" by Yechkalo and Tkachuk [56] aim to provide comprehensive methodical foundations for implementing VR in the professional training of vocational higher education students. The researchers present a detailed model for VR integration, outline key pedagogical conditions, and offer evidence-based recommendations for educators and institutions.

The proposed model consists of five interconnected components: the goal block, theoretical-methodological block, content block, organizational-methodological block, and diagnostic-resultant block (figure 11). The goal block focuses on defining clear, measurable learning objectives that align VR activities with overall curriculum goals and industry skill requirements. The theoretical-methodological block draws on established learning theories while leveraging the unique affordances of VR, incorporating principles like experiential learning, situated learning, and collaborative learning. The content block outlines strategies for designing VR learning content and activities, including realistic modelling, interactive elements, scenario-based learning, and feedback mechanisms. The organizational-methodological block addresses the practical considerations of VR implementation, such as technology infrastructure, instructor training, student orientation, and health & safety protocols. The diagnostic-resultant block emphasizes the importance of ongoing assessment and evaluation to refine and improve VR integration.

The paper also identifies two key pedagogical conditions for effective VR use: motivation for professional activities and integration of VR methodology. Enhancing student motivation through realistic previews of workplaces, low-stakes experimentation, and gamified skill development is crucial. Integrating VR into the curriculum coherently and systematically, rather than treating it as an isolated tool, is essential for maximizing its educational impact.

A particularly promising application of VR in vocational training is the creation of virtual workshops and laboratories. These immersive environments allow students to practice using specialized equipment, conduct experiments, troubleshoot scenarios, collaborate on projects, and explore dangerous or hard-to-access settings—all without the risks and costs associated with physical facilities. Key features of

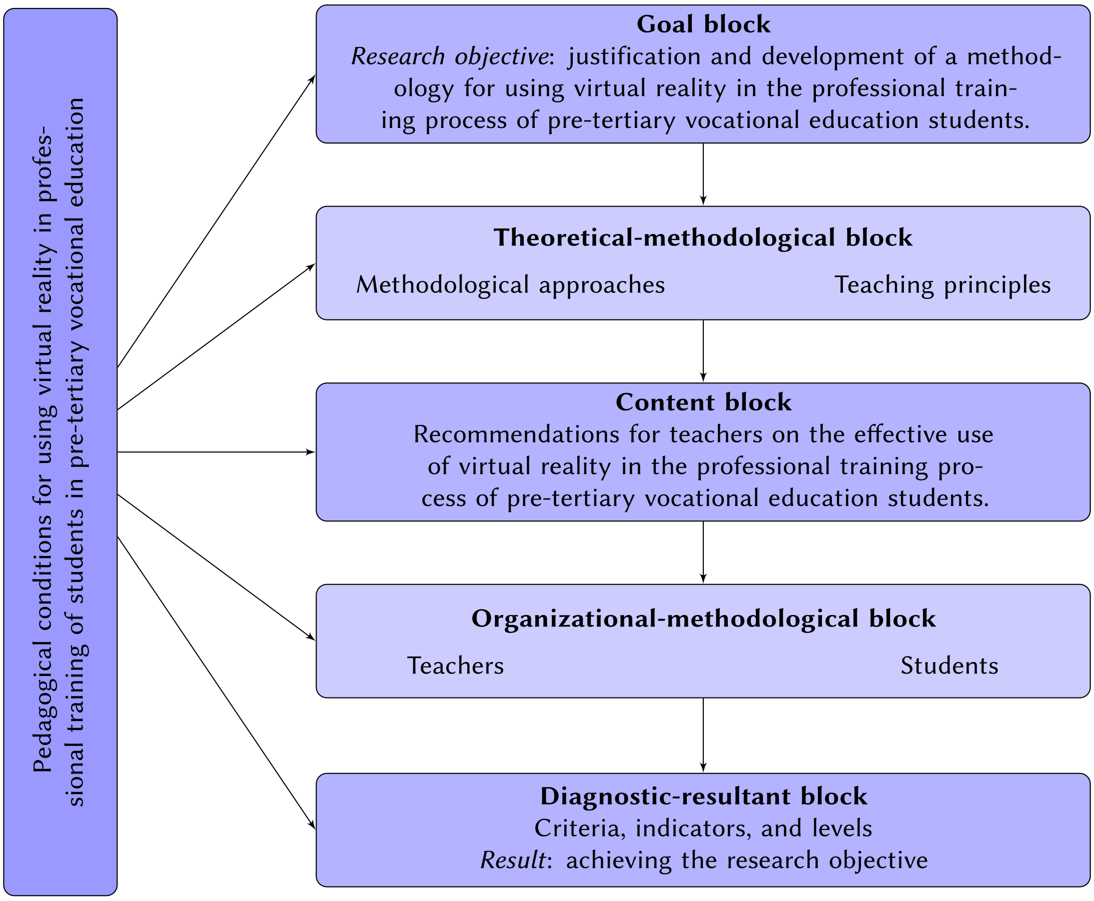

Figure 11: Comprehensive model for integrating VR in vocational higher education [56].

effective virtual workshops include high-fidelity 3D modelling, physics-based interactions, customizable scenarios, data analytics, and multi-user functionality.

The paper provides detailed implementation recommendations, emphasizing the importance of starting with small-scale pilot projects, providing comprehensive instructor training, aligning VR activities with existing curricula, and establishing robust assessment mechanisms. Institutions must also address challenges related to high initial costs, student comfort and well-being, skills transfer assessment, technological obsolescence, equity and access, content development, and ethical considerations.

4. Conclusion

The proceedings of the 6th International Workshop on Augmented Reality in Education (AREdu 2023) offer a comprehensive snapshot of the current state of research and practice in this dynamic field. The papers presented at the workshop demonstrate the creativity, rigour, and passion of a global community of scholars and practitioners committed to harnessing the power of AR to enhance teaching and learning.

From theoretical frameworks and methodological innovations to real-world applications and empirical studies, the contributions span a wide range of topics and contexts, reflecting the diversity and vitality of the field. They showcase the potential of AR to revolutionize education by creating immersive, interactive, and personalized learning experiences that foster engagement, motivation, and deep understanding.

At the same time, the proceedings also highlight the challenges and opportunities that lie ahead. Realizing AR's full promise in education will require sustained investment in research and development, teacher preparation and support, infrastructure and resources, and policies and standards that promote equity and excellence. It will also demand ongoing collaboration and dialogue among diverse stakeholders to ensure that the technology serves the needs and aspirations of all learners.

The Academy of Cognitive and Natural Sciences (https://acnsci.org/), in partnership with Kryvyi Rih State Pedagogical University and Kryvyi Rih National University, had the pleasure of hosting the 6th International Workshop on Augmented Reality in Education (AREdu 2023).

We extend our sincere gratitude to the authors who submitted their papers and the delegates for their active participation and unwavering interest in our workshops, which have provided a platform for the exchange of ideas and innovation. Our heartfelt appreciation goes to the program committee members for their continuous guidance and to the peer reviewers, whose diligent efforts have substantially enhanced the quality of the papers by providing constructive criticisms, improvements, and corrections. We acknowledge and thank the authors for their significant contributions to the workshop's success.

Furthermore, we express our most profound appreciation to the CEUR-WS.org team (https://ceur-ws.org/), the only sponsor of the AREdu workshop series since 2018.

We had excellent presentations and fruitful discussions that broadened our professional horizons, and we trust that all participants derive immense satisfaction from this workshop. We look forward to the day when we will be able to meet again in person under more tranquil and peaceful circumstances.

References

[1] A. E. Kiv, V. N. Soloviev, Preface, in: A. E. Kiv, V. N. Soloviev (Eds.), Proceedings of the 1st International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, October 2, 2018, volume 2257 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018. URL: https://ceur-ws.org/Vol-2257/preface.pdf.

[2] A. E. Kiv, M. P. Shyshkina, S. O. Semerikov, A. M. Striuk, Y. V. Yechkalo, AREdu 2019 - How augmented reality transforms to augmented learning, in: A. E. Kiv, M. P. Shyshkina (Eds.), Proceedings of the 2nd International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, March 22, 2019, volume 2547 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 1–12. URL: https://ceur-ws.org/Vol-2547/paper00.pdf.

[3] O. Y. Burov, A. E. Kiv, S. O. Semerikov, A. M. Striuk, M. I. Striuk, L. S. Kolgatina, I. V. Oliinyk, AREdu 2020 - How augmented reality helps during the coronavirus pandemic, in: O. Y. Burov, A. E. Kiv (Eds.), Proceedings of the 3rd International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, May 13, 2020, volume 2731 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 1–46. URL: https://ceur-ws.org/Vol-2731/paper00.pdf.

[4] S. H. Lytvynova, S. O. Semerikov, A. M. Striuk, M. I. Striuk, L. S. Kolgatina, V. Y. Velychko, I. S. Mintii, O. O. Kalinichenko, S. M. Tukalo, AREdu 2021 - Immersive technology today, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 1–40. URL: https://ceur-ws.org/Vol-2898/paper00.pdf.

[5] S. Papadakis, A. E. Kiv, H. M. Kravtsov, V. V. Osadchyi, M. V. Marienko, O. P. Pinchuk, M. P. Shyshkina, O. M. Sokolyuk, I. S. Mintii, T. A. Vakaliuk, L. E. Azarova, L. S. Kolgatina, S. M. Amelina, N. P. Volkova, V. Y. Velychko, A. M. Striuk, S. O. Semerikov, Unlocking the power of synergy: the joint force of cloud technologies and augmented reality in education, in: S. O. Semerikov, A. M. Striuk (Eds.), Joint Proceedings of the 10th Workshop on Cloud Technologies in Education, and 5th International Workshop on Augmented Reality in Education (CTE+AREdu 2022), Kryvyi Rih, Ukraine, May 23, 2022, volume 3364 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 1–23. URL: https://ceur-ws.org/Vol-3364/paper00.pdf.

[6] S. O. Semerikov, A. M. Striuk, Augmented Reality in Education 2023: innovations, applications, and future directions, CEUR Workshop Proceedings (2024) 1–22.

[7] A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk, First student workshop on computer science & software engineering, CEUR Workshop Proceedings 2292 (2018) 1–10.

[8] R. O. Tarasenko, S. M. Amelina, S. O. Semerikov, V. D. Shynkaruk, Using interactive semantic

networks as an augmented reality element in autonomous learning, Journal of Physics: Conference Series 1946 (2021) 012023. doi:10.1088/1742-6596/1946/1/012023.

[9] I. Georgescu, J. Kinnunen, The role of foreign direct investments, urbanization, productivity, and energy consumption in Finland's carbon emissions: an ARDL approach, Environmental Science and Pollution Research 30 (2023) 87685–87694. doi:10.1007/s11356-023-28680-w.

[10] B. P., G. D., G. F., Using augmented reality devices for remote support in manufacturing: A case study and analysis, Advances in Production Engineering & Management 16 (2021) 418–430. doi:10.14743/apem2021.4.410.

[11] C. Pribeanu, A. Balog, D. D. Iordache, Formative User-Centered Usability Evaluation of an Augmented Reality Educational System, in: J. Cordeiro, B. Shishkov, A. Ranchordas, M. Helfert (Eds.), ICSOFT 2008 - Proceedings of the Third International Conference on Software and Data Technologies, Volume ISDM/ABF, Porto, Portugal, July 5-8, 2008, INSTICC Press, 2008, pp. 65–72.

[12] D. Rodriguez-Andres, M. Mendez-Lopez, M.-C. Juan, E. Perez-Hernandez, A Virtual Object-Location Task for Children: Gender and Videogame Experience Influence Navigation; Age Impacts Memory and Completion Time, Frontiers in Psychology 9 (2018). doi:10.3389/fpsyg.2018.00451.

[13] R. Zender, P. Sander, M. Weise, M. Mulders, U. Lucke, M. Kerres, HandLeVR: Action-Oriented Learning in a VR Painting Simulator, in: E. Popescu, T. Hao, T.-C. Hsu, H. Xie, M. Temperini, W. Chen (Eds.), Emerging Technologies for Education, volume 11984 of *Lecture Notes in Computer Science*, Springer International Publishing, Cham, 2020, pp. 46–51. doi:10.1007/978-3-030-38778-5_6.

[14] G. Kiss, A. Szasz, Analysing of the information security awareness of the economic information technology students, in: 2016 IEEE 17th International Symposium on Computational Intelligence and Informatics (CINTI), 2016, pp. 000213–000218. doi:10.1109/CINTI.2016.7846406.

[15] S. K. Battula, S. Garg, R. Naha, M. B. Amin, B. Kang, E. Aghasian, A blockchain-based framework for automatic SLA management in fog computing environments, The Journal of Supercomputing 78 (2022) 16647–16677. doi:10.1007/s11227-022-04545-w.

[16] A. Kaminskyi, M. Nehrey, N. Rizun, The impact of covid-induced shock on the risk-return correspondence of agricultural etfs, in: A. Kiv (Ed.), Proceedings of the Selected Papers of the Special Edition of International Conference on Monitoring, Modeling & Management of Emergent Economy (M3E2-MLPEED 2020), Odessa, Ukraine, July 13-18, 2020, volume 2713 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 204–218. URL: https://ceur-ws.org/Vol-2713/paper17.pdf.

[17] T. A. Vakaliuk, S. I. Pochtoviuk, Analysis of tools for the development of augmented reality technologies, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 119–130. URL: https://ceur-ws.org/Vol-2898/paper06.pdf.

[18] N. Veretennikova, N. Kunanets, Recommendation Systems as an Information and Technology Tool for Virtual Research Teams, in: N. Shakhovska, V. Stepashko (Eds.), Advances in Intelligent Systems and Computing II, volume 689 of *Advances in Intelligent Systems and Computing*, Springer International Publishing, Cham, 2018, pp. 577–587. doi:10.1007/978-3-319-70581-1_40.

[19] R. O. Tarasenko, S. M. Amelina, Y. M. Kazhan, O. V. Bondarenko, The use of AR elements in the study of foreign languages at the university, in: O. Y. Burov, A. E. Kiv (Eds.), Proceedings of the 3rd International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, May 13, 2020, volume 2731 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 129–142. URL: https://ceur-ws.org/Vol-2731/paper06.pdf.

[20] O. Kodym, T. Martoch, L. Kubac, R. Danel, Z. Neustupa, Usage of virtual reality for presentation of full lifecycle of opencast mines with support of internet of things, in: 12th International Multidisciplinary Scientific GeoConference and EXPO - Modern Management of Mine Producing, Geology and Environmental Protection, SGEM 2012, volume 3, 2012, pp. 297–304.

[21] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, V. N. Soloviev, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, V. R. Ruban, Mask and Emotion: Computer

Vision in the Age of COVID-19, in: Digital Humanities Workshop, DHW 2021, Association for Computing Machinery, New York, NY, USA, 2022, p. 103–124. doi:10.1145/3526242.3526263.
[22] H. Javaheri, A. Gruenerbl, E. Monger, M. Gobbi, P. Lukowicz, Stayin' Alive: An Interactive Augmented: Reality CPR Tutorial, in: Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers, UbiComp '18, Association for Computing Machinery, New York, NY, USA, 2018, p. 365–368. doi:10.1145/3267305.3267569.
[23] G. Rotidi, K. Kedraka, E.-M. Frementiti, C. Kaltsidis, University Pedagogy in Greece: Pedagogical Needs of Greek Academics from Ionian University, in: A. Kavoura, E. Kefallonitis, P. Theodoridis (Eds.), Strategic Innovative Marketing and Tourism, Springer Proceedings in Business and Economics, Springer International Publishing, Cham, 2020, pp. 737–744. doi:10.1007/978-3-030-36126-6_81.
[24] O. H. Kolgatin, L. S. Kolgatina, N. S. Ponomareva, Computational modelling of stochastic processes for learning research, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 9th Illia O. Teplytskyi Workshop on Computer Simulation in Education (CoSinE 2021) co-located with 17th International Conference on ICT in Education, Research, and Industrial Applications: Integration, Harmonization, and Knowledge Transfer (ICTERI 2021), Kherson, Ukraine, October 1, 2021, volume 3083 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 1–15. URL: https://ceur-ws.org/Vol-3083/paper296.pdf.
[25] G. Chuiko, O. Dvornik, Y. Darnapuk, Y. Krainyk, Oxygen Saturation Variability: Healthy Adults, in: 2019 XIth International Scientific and Practical Conference on Electronics and Information Technologies (ELIT), 2019, pp. 72–75. doi:10.1109/ELIT.2019.8892319.
[26] S. Papadakis, A. E. Kiv, H. M. Kravtsov, V. V. Osadchyi, M. V. Marienko, O. P. Pinchuk, M. P. Shyshkina, O. M. Sokolyuk, I. S. Mintii, T. A. Vakaliuk, L. E. Azarova, L. S. Kolgatina, S. M. Amelina, N. P. Volkova, V. Y. Velychko, A. M. Striuk, S. O. Semerikov, Unlocking the power of synergy: the joint force of cloud technologies and augmented reality in education, in: S. O. Semerikov, A. M. Striuk (Eds.), Joint Proceedings of the 10th Workshop on Cloud Technologies in Education, and 5th International Workshop on Augmented Reality in Education (CTE+AREdu 2022), Kryvyi Rih, Ukraine, May 23, 2022, volume 3364 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 1–23. URL: https://ceur-ws.org/Vol-3364/paper00.pdf.
[27] A. E. Kroshilin, V. N. Kukharenko, B. I. Nigmatulin, Particle deposition on a channel wall in a turbulent disperse flow with gradient, Fluid Dynamics 20 (1985) 542–547. doi:10.1007/BF01049887.
[28] S. H. Lytvynova, S. O. Semerikov, A. M. Striuk, M. I. Striuk, L. S. Kolgatina, V. Y. Velychko, I. S. Mintii, O. O. Kalinichenko, S. M. Tukalo, AREdu 2021 - Immersive technology today, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 1–40. URL: https://ceur-ws.org/Vol-2898/paper00.pdf.
[29] S. O. Semerikov, M. M. Mintii, I. S. Mintii, Review of the course "Development of Virtual and Augmented Reality Software" for STEM teachers: implementation results and improvement potentials, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 159–177. URL: https://ceur-ws.org/Vol-2898/paper09.pdf.
[30] S. O. Semerikov, A. M. Striuk, T. A. Vakaliuk, A. Morozov, Quantum information technology on the Edge, in: S. O. Semerikov (Ed.), Joint Proceedings of the Workshops on Quantum Information Technologies and Edge Computing (QuaInT+doors 2021), Zhytomyr, Ukraine, April 11, 2021, volume 2850 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 1–15. URL: http://ceur-ws.org/Vol-2850/paper0.pdf.
[31] P. Nechypurenko, O. Evangelist, T. Selivanova, Y. O. Modlo, Virtual Chemical Laboratories as a Tools of Supporting the Learning Research Activity of Students in Chemistry While Studying the Topic "Solutions", in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International

Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 984–995. URL: https://ceur-ws.org/Vol-2732/20200984.pdf.

[32] M. V. Marienko, Y. H. Nosenko, M. P. Shyshkina, Smart systems of open science in teachers' education, Journal of Physics: Conference Series 2288 (2022) 012035. doi:10.1088/1742-6596/2288/1/012035.

[33] V. P. Oleksiuk, J. A. Overko, O. M. Spirin, T. A. Vakaliuk, A secondary school's experience of a cloud-based learning environment deployment, in: T. A. Vakaliuk, V. V. Osadchyi, O. P. Pinchuk (Eds.), Proceedings of the 2nd Workshop on Digital Transformation of Education (DigiTransfEd 2023) co-located with 18th International Conference on ICT in Education, Research and Industrial Applications (ICTERI 2023), Ivano-Frankivsk, Ukraine, September 18-22, 2023, volume 3553 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 93–109. URL: https://ceur-ws.org/Vol-3553/paper7.pdf.

[34] K. Osadcha, V. Osadchyi, S. Semerikov, H. Chemerys, A. V. Chorna, The Review of the Adaptive Learning Systems for the Formation of Individual Educational Trajectory, in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 547–558. URL: https://ceur-ws.org/Vol-2732/20200547.pdf.

[35] D. S. Shepiliev, Y. O. Modlo, Y. V. Yechkalo, V. V. Tkachuk, M. M. Mintii, I. S. Mintii, O. M. Markova, T. V. Selivanova, O. M. Drashko, O. O. Kalinichenko, T. A. Vakaliuk, V. V. Osadchyi, S. O. Semerikov, WebAR development tools: An overview, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 3rd Workshop for Young Scientists in Computer Science & Software Engineering (CS&SE@SW 2020), Kryvyi Rih, Ukraine, November 27, 2020, volume 2832 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 84–93. URL: http://ceur-ws.org/Vol-2832/paper12.pdf.

[36] L. F. Panchenko, H. O. Korzhov, A. O. Khomiak, V. Y. Velychko, V. N. Soloviev, Social dimension of higher education: definition, indicators, models, in: A. E. Kiv, S. O. Semerikov, M. P. Shyshkina (Eds.), Proceedings of the 9th Workshop on Cloud Technologies in Education, CTE 2021, Kryvyi Rih, Ukraine, December 17, 2021, volume 3085 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 124–138. doi:10.55056/CTE.108.

[37] T. A. Vakaliuk, V. V. Osadchyi, O. P. Pinchuk, From the digital transformation strategy to the productive integration of technologies in education and training: Report 2023, in: T. A. Vakaliuk, V. V. Osadchyi, O. P. Pinchuk (Eds.), Proceedings of the 2nd Workshop on Digital Transformation of Education (DigiTransfEd 2023) co-located with 18th International Conference on ICT in Education, Research and Industrial Applications (ICTERI 2023), Ivano-Frankivsk, Ukraine, September 18-22, 2023, volume 3553 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 1–8. URL: https://ceur-ws.org/Vol-3553/paper00.pdf.

[38] V. Tkachuk, S. Semerikov, Y. V. Yechkalo, S. Khotskina, V. N. Soloviev, Selection of Mobile ICT for Learning Informatics of Future Professionals in Engineering Pedagogy, in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 1058–1068. URL: https://ceur-ws.org/Vol-2732/20201058.pdf.

[39] V. B. Shapovalov, Y. B. Shapovalov, Z. I. Bilyk, A. P. Megalinska, I. O. Muzyka, The Google Lens analyzing quality: an analysis of the possibility to use in the educational process, in: A. E. Kiv, M. P. Shyshkina (Eds.), Proceedings of the 2nd International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, March 22, 2019, volume 2547 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 117–129. URL: https://ceur-ws.org/Vol-2547/paper09.pdf.

[40] A. M. Striuk, S. O. Semerikov, The Dawn of Software Engineering Education, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 2nd Student Workshop on Computer Science & Software Engineering (CS&SE@SW 2019), Kryvyi Rih, Ukraine, November 29, 2019, volume 2546 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 35–57. URL: http://ceur-ws.org/Vol-2546/paper02.pdf.

[41] N. Kushnir, A. Manzhula, N. Valko, Future and Experienced Teachers Should Collaborate on ICT Integration, in: V. Ermolayev, H. C. Mayr, M. Nikitchenko, A. Spivakovsky, G. Zholtkevych (Eds.), Information and Communication Technologies in Education, Research, and Industrial Applications, volume 469 of *Communications in Computer and Information Science*, Springer International Publishing, Cham, 2014, pp. 217–237. doi:10.1007/978-3-319-13206-8_11.

[42] K. Vlasenko, S. Volkov, I. Sitak, I. Lovianova, D. Bobyliev, Usability analysis of on-line educational courses on the platform "Higher school mathematics teacher", E3S Web of Conferences 166 (2020) 10012. doi:10.1051/e3sconf/202016610012.

[43] V. Tkachuk, Y. V. Yechkalo, S. Semerikov, M. Kislova, V. Khotskina, Exploring Student Uses of Mobile Technologies in University Classrooms: Audience Response Systems and Development of Multimedia, in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 1217–1232. URL: https://ceur-ws.org/Vol-2732/20201217.pdf.

[44] L. V. Pavlenko, M. P. Pavlenko, Using native virtualization technologies for teaching IP telephony to future IT specialists, CEUR Workshop Proceedings (2024) 23–34.

[45] L. V. Vasylieva, D. Y. Mikhieienko, I. A. Getman, Integration of laboratory equipment in remote learning environments, CEUR Workshop Proceedings (2024) 35–44.

[46] M. V. Moiseienko, N. V. Moiseienko, O. O. Lavrentieva, Developing pre-service teachers' digital competence through informatics disciplines in teacher education programs, CEUR Workshop Proceedings (2024) 45–52.

[47] V. Y. Pazdrii, V. O. Kuprievych, Implementing business simulation games for strategic management training of educational leaders in Ukraine, CEUR Workshop Proceedings (2024) 53–62.

[48] M. V. Nehrey, L. M. Zomchak, The educational technology landscape in Ukraine, CEUR Workshop Proceedings (2024) 63–71.

[49] S. O. Semerikov, T. A. Vakaliuk, P. P. Nechypurenko, I. S. Mintii, O. V. Bondarenko, Shifting sands: analyzing trends in educational technology research published in Educational Technology Quarterly (2021-2023), CEUR Workshop Proceedings (2024) 72–82.

[50] S. S. Korniienko, P. V. Zahorodko, A. M. Striuk, A. I. Kupin, S. O. Semerikov, A systematic review of gamification in software engineering education, CEUR Workshop Proceedings (2024) 83–95.

[51] Y. V. Yechkalo, V. V. Tkachuk, K. A. Shurupova, V. M. Zinchenko, A. V. Puhach, Gamification in higher education: methodology, CEUR Workshop Proceedings (2024) 96–106.

[52] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, Designing an immersive cloud-based educational environment for universities: a comprehensive approach, CEUR Workshop Proceedings (2024) 107–116.

[53] T. H. Kramarenko, O. S. Pylypenko, M. V. Moiseienko, Enhancing mathematics education with GeoGebra and augmented reality, CEUR Workshop Proceedings (2024) 117–126.

[54] V. Y. Velychko, E. H. Fedorenko, The utility of free software in teaching of mathematics, physics and computer science for pre-service teachers, CEUR Workshop Proceedings (2024) 127–133.

[55] I. V. Barkatov, V. S. Farafonov, V. O. Tiurin, S. S. Honcharuk, A. A. Lozko, V. V. Marushchenko, K. V. Korytchenko, V. I. Barkatov, R. F. Muravlyov, Interactive 3D visualizations for studying combat experiences and life cycles, CEUR Workshop Proceedings (2024) 134–142.

[56] Y. V. Yechkalo, V. V. Tkachuk, Methodical foundations and implementation strategies for virtual reality in professional training of vocational higher education students, CEUR Workshop Proceedings (2024) 143–153.

Using native virtualization technologies for teaching IP telephony to future IT specialists

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Abstract

This paper explores the use of virtualization technologies for teaching IP telephony to future IT specialists. It defines the requirements for students' professional training in this field and identifies the components of a network training laboratory for IP telephony. It also analyzes the modern approaches to virtualization technologies and their advantages for learning IP telephony. The paper proposes native virtualization as a suitable solution for creating a virtual training laboratory using VirtualBox software. It reports the results of a pedagogical experiment that confirmed the effectiveness of the developed virtual laboratory and repository of virtual hosts for teaching IP telephony. The paper highlights the benefits of virtual machines for student mobility and remote learning, especially during the pandemic and war.

Keywords

IP telephony, virtualization technologies, VirtualBox, network training laboratory, professional training

1. Introduction

The education of future IT specialists requires the use of modern learning technologies, including information technologies. The rapid development and improvement of hardware and software platforms pose a challenge for higher education institutions to keep up with the current requirements and demands of society in the field of information technology [1].

This challenge is especially evident in the teaching of the discipline of "IP telephony in computer networks" to future IT specialists. To prepare them effectively, they need to acquire the following knowledge and skills:

- installing, operating and maintaining various operating systems in network environments, both local and global;
- installing, configuring, operating and maintaining IP telephony software in network environments, both local and global.

One of the possible solutions to this challenge is the introduction of virtualization technology in the educational process.

However, the implementation and application of virtualization technology in the education of future IT professionals face many organizational, methodological and technical problems. There is no unified concept or approach to its use. The development and application of virtualization technology in different domains of computer science have been studied by Khomenko et al. [2], Lunsford [3], Osadchyi et al. [4], Ray and Srivastava [5], Stefanek [6], Yan [7], Yuan and Cross [8], Yuan et al. [9].

The use of virtualization in the teaching of information technology has been investigated by Chamberlin et al. [10], Barrionuevo et al. [11], Khomenko et al. [2], Oleksiuk and Oleksiuk [12], Popel et al. [13], Segeč et al. [14], Seidametova et al. [15], Soler [16], Vakaliuk [17], Vakaliuk et al. [18], Vlasenko et al. [19], Yuan et al. [20, 21].

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The use of virtualization in the training IP telephony to future IT specialists has been explored by Abubakr et al. [22], Kaul and Jain [23], Moravcik and Kontsek [24], Rendon Schneir and Plückebaum [25], Setiawan et al. [26].

The *aim* of this paper is to analyze the existing virtualization technologies and their potential for teaching IP telephony in computer networks to future IT specialists.

2. Reasoning for choosing a virtualization system for learning IP telephony

Training of future IT specialists in accordance with the state standard of higher education involves the formation of a number of professional competencies [27, 28, 29, 30, 31, 32]: the ability to use operating and intelligent systems in solving practical problems, taking into account the protection of information in computer systems and networks; ability to use programming languages and software engineering in solving problems and tasks of social and professional nature; ability to analyze, debug, use and develop human-machine interaction based on computer architecture and organization.

They are formed during the study of a number of professional-oriented disciplines, one of which is "IP telephony in computer networks".

In accordance with the purpose of the study, we will consider virtualization technologies and identify prospects for their application to train future IT professionals in IP telephony in computer networks.

The study of "IP telephony in computer networks" uses two Asterisk servers based on Debian or Ubuntu Linux and at least two client personal computers with Windows operating systems and IP telephony software installed as a network training laboratory. This hardware and software are necessary to model the network interaction of IP telephony clients and servers using SIP, IAX2, H.323 protocols. One of the areas of a network laboratory development and implementation for the study of IP telephony is the application of virtualization.

The concept of virtualization appeared in the 1970s. It was understood as the transfer of physical resources of a computer into a virtual one with the help of specialized software, abstract layers allow creating several virtual machines on one physical machine, each virtual machine being able to work with its operating system [33].

Virtualization, as a concept, is used for two technologies that are fundamentally different: resource virtualization and platform virtualization. Resource virtualization, in contrast to platform virtualization, has a broader meaning and combines a large number of different approaches aimed at improving the usability of users with information systems in general. In our study, we will build on the concept of platform virtualization, as related technologies are evolving and are effective in achieving the goals of training future IT professionals.

Platform virtualization is understood as the creation of software systems based on existing hardware and software complexes. A system that provides hardware resources and software is called a host, and the systems it simulates are called guest systems. There are several types of virtualization platforms, each of which has its own approach to the concept of "virtualization". They are mainly determined by how full the hardware simulation [34].

We will consider virtualization with full emulation. This approach completely virtualizes all the hardware while keeping the guest operating system unchanged [35]. This allows you to simulate different hardware architectures. For example, you can run virtual machines with guest systems for x86 processors on platforms with a different architecture. Examples of software for complete simulation are: Bochs, Pearpc and QEMU.

The main disadvantage of this approach is that the simulated hardware significantly slows down the performance of the guest system, which makes interaction with it very inconvenient. Therefore, such products should not be used as a basis for developing a virtual training laboratory to study "IP telephony in computer networks" discipline.

Let's consider paravirtualization as a basis for the development of a virtual training laboratory for the study of the "IP telephony in computer networks" discipline. While using paravirtualization, the hardware is not simulated, a special software interface (API) is used to interact with the guest operating system at the level of RAM pages.

This approach requires modification of the guest system code. A significant number of hardware and software developers have doubts about the prospects of this approach to virtualization [36], because today all decisions of hardware manufacturers regarding virtualization are aimed at systems with native virtualization. In addition, it should be noted the difficulty of deploying new instances of virtual machines for users. Therefore, the use of paravirtualization software in learning IP telephony in computer networks is impractical. Examples of paravirtualization are Xen, L4, TRANGO, WindRiver and XtratuMhypervisors.

We will consider partial (native) virtualization in the context of our study. In this case, only the required amount of hardware to run an isolated virtual machine is simulated [37]. This approach allows you to run guest operating systems designed only for the same architecture as the host.

In this way, multiple samples of guest systems can be run simultaneously, allowing you to simulate a computer network with IP telephony servers and clients on a single personal computer. This type of virtualization can significantly increase the speed of guest systems compared to full emulation and it is widely used today.

Beside this, the distribution of already established guest systems among users is quite simple and possible only on the basis of copying files. Disadvantages of this type of virtualization include the dependence of virtual machines on the architecture of the hardware platform, but for the "IP telephony in computer networks" discipline we use operating systems and software for x86 architecture. Examples of products for native virtualization: VMware Workstation, Virtualbox, Parallels Workstation and others, including server solutions (VMware Server, Microsoft Virtual Server, VMware ESX Server, VirtualIron and Microsoft Hyper V).

We will consider the virtualization of the operating system level and identify opportunities for its use to train future IT professionals in IP telephony in computer networks. The guest system, in this case, shares the use of one kernel of the host operating system with other guest systems [7]. The virtual machine provides an environment for applications that run in isolation. This type of virtualization is used in the organization of virtual hosting systems, when you need to support multiple virtual client servers within one instance of the kernel.

This technology allows you to isolate each virtual system and deprive them of the ability to influence each other. Examples of operating system layer virtualization include: iCoreVirtualAccounts, Linux-VServer, LXC, OpenVZ, ParallelsVirtuozzoContainers, FreeBSDJail and sysjail.

We will consider virtualization of the application level. This type of virtualization involves the creation of separate containers for software isolation. The container includes all the necessary elements for the correct operation of the software: registry files, configuration files, user and system objects. As a result, the user receives an application that does not require installation on a similar platform.

Transferring the software to another computer will create a virtual environment for it, and the virtualization program resolves conflicts between the software and the operating system and other applications. Examples of such an approach are: Thinstall, Altiris, Trigence, Microsoft ApplicationVirtualization (App-V). Using application-level virtualization to train IP telephony to future IT professionals is impractical, due to the need to create a computer network model with separate servers and workstations rather than software.

So, we can affirm that one of the best solutions for the introduction of virtualization in the methodology of teaching IP telephony discipline in the computer networks will be the technology of native virtualization. This can be explained with the ability to use virtual machines in independent and classroom work of students, easy export of ready-made solutions and the ability to create a complex network infrastructure among downloaded virtual machines.

Let's consider the problem of choosing the specific software for native virtualization in order to use it to teach IP telephony in more detail. Let's analyze the possibility of using one of the three popular solutions for virtualization in the workplace: VMware Workstation, Parallels Workstation and VirtualBox.

VMware company is one of the best known in the high technology industry. It develops effective software in the field of virtualization. Their implementation of server software is widely used in virtual data centers and personal computers in business and industry.

VMware has two types of desktop software: VMware Workstation and VMwarePlayer. Every virtual client supports and works with virtual machines flawlessly. But the Workstation option has more features, namely: support for two monitors, integration of the Unity interface, and most importantly the ability to create virtual machines. The Player version only allows you to run and execute previously created virtual machines.

Teaching IP telephony in computer networks involves students creating their own virtual machines, so VMwarePlayer software cannot be used due to the existing restrictions on creating new virtual machines.

VMware Workstation functionality allows you to use it on computers running Windows and Linux operating systems. The wizard for installing and debugging new virtual machines is simple and intuitive, and the default settings for specific operating systems are selected quite well. This allows students not to spend a lot of study time mastering software management skills.

Unity virtual interface integration allows you to include virtual machine elements directly into the host operating system interface. That is, icons and windows from a Windows virtual machine will work with icons and windows from the Ubuntu operating system. However, the use of Unity leads to a significant slowdown of virtual machines and complicates their use.

Parallels company is developing a software product for PC virtualization – Parallels Workstation. It solves the main task of virtualization – the simultaneous launch of multiple operating systems on a single computer running Windows or Linux. This product uses features designed for professionals in the field of local and online applications, software testing professionals and web designers. It can also be widely used for educational purposes.

During Parallels Workstation development the requirements for the product by IT specialists were considered. This software can work with more than 25 major operating systems – both 32-bit and 64-bit. High performance of Parallels Workstation is compatible with Intel VT-x2 virtualization technology and the use of a hypervisor.

However, owing to Controlled Native Execution (CNE) technology, Parallels Workstation allows you to run guest operating systems on older computers whose processors do not have hardware support for virtualization. Parallels Workstation's professional user interface offers many options for creating and configuring virtual machines, but an untrained professional will not be able to quickly create and install a virtual machine, making it difficult to use Parallels Workstation to teach IP telephony in computer networks.

VirtualBox is open source software, i.e. free of charge. Individual commercial functional elements are downloaded in the form of plug-ins. VirtualBox combines features of solutions for both servers and workstations. The first includes technologies of "balloon" dynamic redistribution and reduplication of RAM in a virtual machine on 64-bit hosts, iSCSI support, GUI-free mode and an efficient method of remote access to virtual machines through a shared RDP-server (VRDP, VirtualBox Remote Display Protocol). The second is high-quality support for USB equipment, including USB 2.0, as well as 2D and 3D acceleration in virtual machines due to the resources of the host graphics adapter.

VirtualBox can provide virtualization in a purely software mode or by using hardware support in modern processors. It uses disassembly of guest OS code and a number of other techniques, combining them.

While creating new virtual machines, the developers of VirtualBox managed to protect their users from possible problems and the need to understand the technical details. In most cases, it is sufficient to agree with the default settings, adjusting only the necessary and obvious of them, say, the amount of RAM.

In this case, the program will to some extent control the correctness of the selected parameters and, if necessary, make corrections or issue appropriate warnings. It is no coincidence that all the most subtle settings and actions can be performed exclusively from the command line, which, of course, requires the user to have some understanding of what is happening. These features are very convenient to use while creating and debugging virtual machines when learning IP telephony in computer networks.

As one can see from table VirtualBox software supports multiple operating systems, allows you to connect up to 36 network adapters to a virtual machine and is distributed free of charge. All this points to the benefits of using VirtualBox as the main virtualization tool in the development of a network lab for training future IT professionals in IP telephony in computer networks.

Table 1
Features of VMware Workstation, Parallels Workstation and Virtualbox.

Feature	VMware Workstation	Parallels Workstation	VirtualBox
Supported host operational systems	Windows, Linux, Mac OS X	Windows, Linux, MacOS X	Windows, Windows Server, Linux, Mac OS X, Solaris, OpenSolaris, FreeBSD
Guest operational systems	DOS, Windows, Linux, FreeBSD, Solaris	DOS, Windows, Linux, OS/2	DOS, Windows, Windows Server, Linux, OpenBSD, FreeBSD, OS/2, Solaris, OpenSolaris, others
Network adapters	before 4	before 5	before 36
Virtual disk controllers	IDE or SCSI	IDE (before 4)	IDE or SATA (before 32 disks) or SCSI
USB support	Yes	Yes	Yes
3D acceleration	Limited	No	Yes (OpenGL)
Remote access to the virtual machine	Limited	No	Built-in RDP server
Remote USB support	No	No	Yes
Shared folders	Yes	Yes	Yes
Open software	No	No	Yes
License cost	Workstation for Windows/Linux approximately $199	Workstation for Windows/Linux - $49.99	Free of charge

3. Repository of virtual machines for teaching IP telephony

The content of the discipline "IP telephony in computer networks" involves a series of laboratory work:

1. Installing Asterisk and Free PBX.
2. Basic configuration of the IP telephony server.
3. Configure Asterisk to work with the SIP protocol.
4. Configure the Asterisk dial plan.
5. Calls management in Asterisk.
6. Voice services and menus in Asterisk.
7. Integration of Asterisk into the organization corporate network.

Two servers and several clients are required to perform laboratory work. Virtual hosts in the VirtualBox environment are created as servers. One core, 512 MB of RAM and 10 Gb on the virtual

HDD are allocated for the Virtual Server. The client virtual hosts configuration has 1 Gb of RAM and Windows 7 Home and LinuxMint 18 operating systems.

The server virtual hosts have the Ubuntu 18.04 and AsteriskFreePBX 15 operating systems installed.

Client virtual hosts have software for IP telephony using the SIP protocol – LinphoneDesktop 4 (https://www.linphone.org). This program is open and free. It works in Windows, Linux and MacOS operating systems.

Two IP telephony servers are required to simulate the interaction of server hosts on the Internet. Client hosts are used to test IP telephony features on users' devices (figure 1).

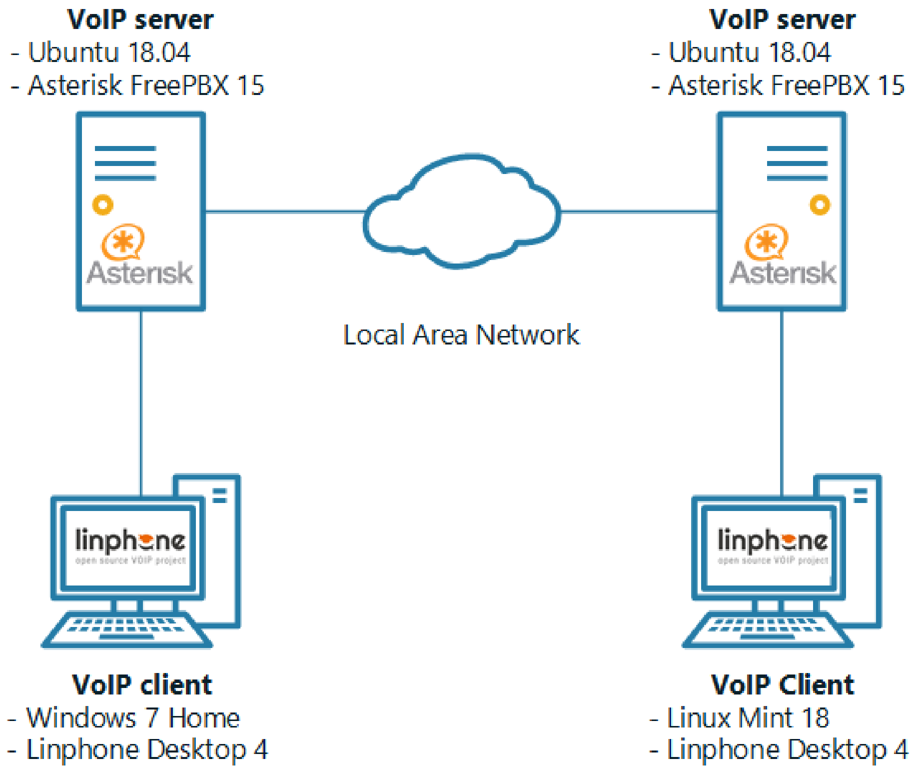

Figure 1: Virtual laboratory of IP telephony.

A set of virtual machines for application in VirtualBox has been prepared for each laboratory work. The developed virtual machines are placed on the internal server of Berdyansk State Pedagogical University. Students can download the required images of virtual machines to perform lab work at any time.

4. The results of the experimental research of virtualization technologies introduction in training of IP telephony

The introduction of virtualization technologies in the training of future IT specialists involves conducting experimental research. The purpose of the pedagogical experiment is to test the research hypothesis: the use of virtualization technologies to teach IP telephony to future IT professionals will help increase the level of knowledge acquisition and skills in the field of IP telephony and computer networks.

The offered methodological approach to the application of virtualization technologies for training IP telephony of future IT specialists should provide the solution of the following tasks:

- software application for virtualization of servers and clients of IP telephony;
- systematic solution of debugging software problems and IP telephony protocols with the use of native virtualization;
- training time increasing to work with a network laboratory for the study of IP telephony.

Students of Berdyansk State Pedagogical University studying in the specialties 015 Professional Education (Computer Technologies) and 015 Professional Education (Digital Technologies) were involved in the experiment. The plan of the experiment provided for the creation of control and experimental groups. The experimental group consisted of 35 students and the control group of 39 students accordingly. Selection for control and experimental groups was carried out immediately before the study of "IP telephony in computer networks" discipline.

Classes in the control group were conducted using a hardware network laboratory. The method of conducting classes in such a laboratory provided for the organization of students' access to the equipment according to the schedule.

The organization of the educational process in the experimental group involved the application of virtualization technologies using the VirtualBox software and the developed repository of virtual machines. Virtual machines were organized according to the educational tasks of the discipline and were configured to perform specific practical tasks for setting up network software for IP telephony.

The success of the pedagogical experiment was insured by the use of such research methods that guarantee a reliable result. The following methods of pedagogical research were chosen: pedagogical observation at all stages of the experiment, tests, analysis of laboratory work, analysis of test results in the experimental and control groups.

The experiment studied the dynamics of the knowledge acquisition level and skills development in the field of IP telephony technologies and computer networks. The experimental technique involved the use of virtualization technologies at all stages of learning:

- while studying new material, as a system for demonstrating the features of setting up technologies and protocols of IP telephony;
- in consolidating the studied material, as a mean of developing skills in the field of IP telephony;
- in independent work, as an environment for the implementation of a professionally-oriented project to configure IP telephony servers in the corporate network of the enterprise.

Two tests were conducted to test the effectiveness of the virtualization technology implementation. The first test was conducted at the beginning of the study of the discipline. The purpose of this test was to determine the readiness of students of control and experimental groups to study IP telephony and covered the issues of installation, configuration and administration of server operating systems and networks. The test consisted of fourteen basic level tasks and three advanced tasks.

The second test was conducted at the end of the study of "IP telephony in computer networks" discipline. It consisted of ten basic tasks and five advanced tasks.

A comparison of students' knowledge acquisition level and skills development in the field of network technology and administration of server operating systems at the beginning of learning "IP telephony in computer networks" discipline revealed similarities in the levels of knowledge acquisition and skills of students in control and experimental groups.

A comparison of the results obtained after studying the discipline "IP telephony in computer networks" revealed differences between the levels of knowledge acquisition and skills formation in the control and experimental groups.

Table 2 shows the results of control works at the beginning and at the end of the experiment in the control and experimental groups.

Comparative analysis of tests results allows us to conclude about the positive dynamics of the knowledge acquisition level and skills in the field of IP telephony in both groups. In the experimental group the dynamics is more pronounced: a 14% increase in the share of students who coped with the task from 75 to 90% of the total (5% in the control group), a 19% decrease in the share of students who coped with tasks from 50 to 75% of the total number of tasks (in the control group increased by 5%) (figure 2).

The share of students in the experimental group who coped with more than 50% of advanced tasks increased by 40% (in the control group the indicator hasn't changed). Statistical parameters of the experimental results are shown in table 3.

Table 2
The results of tests hold at the begging and at the end of the experiment.

	Before the experiment		After the experiment	
	Control group	Experimental group	Control group	Experimental group
Whole results of the test				
Managed with the test (%): including	90	94	90	94
• more than 90% from the whole work volume	5	9	10	14
• from 75 to 90% from the whole work volume	13	20	13	34
• from 50 to 75% from the whole work volume	62	65	67	46
• less than 50% from the whole work volume	20	6	10	6
Tasks of advanced level				
A part of students that have done:				
• more than 50% of the tasks of advanced level	5	14	5	54
• less than 50% of the tasks of advanced level	13	17	26	29
• those, who haven't reached the tasks of advanced level	82	79	69	17

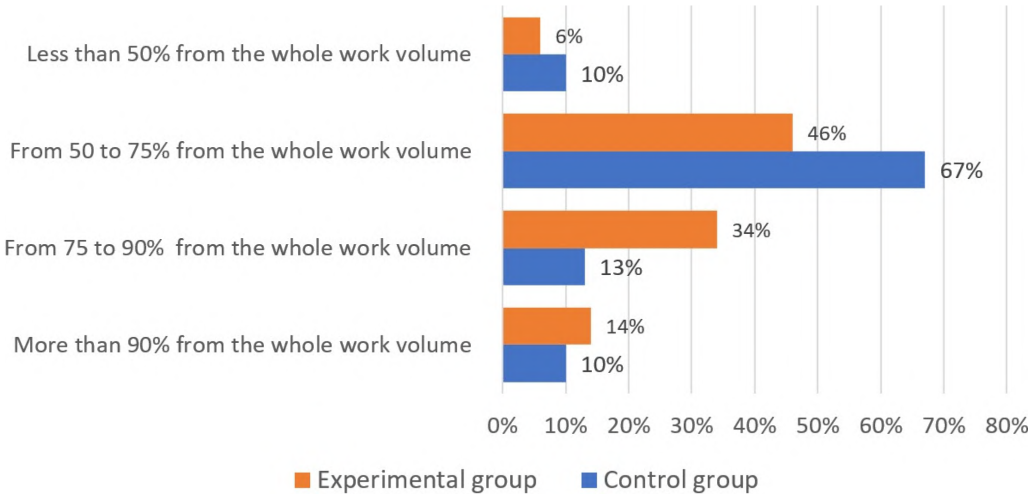

Figure 2: The results of test hold at the end of the experiment.

Analysis of the data in table 3 allows us to say about the positive dynamics in both groups, but in the experimental group the dynamics is more pronounced: the average score for the control work increased by 1.57 (in the control group by 0.85). In the Experimental Group, the median sample increased by 2 points. In the control group, the median increased by only 1 point.

Let's test the hypothesis of a normal sample distribution. We use Pearson's criterion for this. We formulate working hypotheses:

- H_0 – the empirical distribution is a subject to the normal distribution law,
- H_1 – the empirical distribution is a subject to another distribution law.

Table 3
Statistical parameters of knowledge acquisition levels and skills formation in IP telephony in the control and experimental groups before and after the experiment.

Parameters	Control group before the experiment started	Control group after the held experiment	Experimental group before the experiment started	Experimental group after the held experiment
Sample volume	39	39	35	35
Average	12.85	13.46	13.70	15.03
Median	12	13	13	15

The results of the hypothesis test are shown in table 4.

Table 4
The results of testing the hypothesis of the sample distribution normality.

Group	Before the experiment		
Control group	$\chi^2_{empirical}$ 16.64	$\chi^2_{critical}$ 19.68	Accepted hypothesis H_0
Experimental group	$\chi^2_{empirical}$ 17.60	$\chi^2_{critical}$ 18.30	Accepted hypothesis H_0
	After the experiment		
Control group	$\chi^2_{empirical}$ 12.56	$\chi^2_{critical}$ 18.30	Accepted hypothesis H_0
Experimental group	$\chi^2_{empirical}$ 9.96	$\chi^2_{critical}$ 19.68	Accepted hypothesis H_0

Since it was found that all distributions obey the normal law, Student's criterion was chosen for further comparison of the samples (table 5). This will help to determine whether the level of knowledge acquisition and skills development in the field of IP telephony differ in the control and experimental groups. For this purpose working hypotheses were formulated:

- H_0 – levels of knowledge acquisition and skills development in the field of IP telephony of the two groups do not differ.
- H_1 – levels of knowledge acquisition and skills in the field of IP telephony in the two groups are different.

Table 5
The results of statistical test of hypothesis.

Before the experiment		
$t_{empirical}$ 0.8	$t_{critical}$ 1.99	Accepted hypothesis H_0
After the experiment		
$t_{empirical}$ 2.3	$t_{critical}$ 1.99	Accepted hypothesis H_1

The obtained results indicate that at the level of significance $\alpha = 0.05$ the levels of knowledge acquisition and skills formation in the control and experimental group before the experiment coincide and differ after the experiment.

So, the results of the pedagogical experiment indicate that the research hypothesis has been confirmed, namely, the use of virtualization technologies to teach IP telephony to future IT specialists helps to increase the level of knowledge acquisition and skills in the field of IP telephony and computer networks.

5. Conclusions

Virtualization technologies were originally designed for software development and testing purposes. However, they can also be used for educational purposes in the field of information technology.

This paper has shown the benefits of using virtualization in the educational process with VirtualBox, in the discipline of "IP telephony in computer networks":

- the ability to run different operating systems on the same host and enable network interaction among them for implementing IP telephony service;
- the ability to isolate and control potentially risky actions of the operator or software products. In this case, the virtual machine acts as a safe and flexible laboratory platform for the student;
- the ability to create various hardware configurations for simulating network interaction scenarios in the study of IP telephony in computer networks. The students can use predefined hardware configurations to test the performance of Asterisk servers under different conditions. They can also perform various practical experiments with software and hardware components;
- the ability to create repositories of ready-to-use virtual machines with guest operating systems configured according to the specific laboratory tasks. The students can use these virtual machines for learning and research purposes in the field of IP telephony. The recovery of the system from a saved state is fast and easy in case of any damage;
- the ability to run multiple virtual machines connected to a virtual network on a single physical computer. This feature provides significant capabilities for creating virtual network models among multiple systems on a single host;
- the ability to increase student mobility by exporting and moving virtual machines to another computer. The students can start their virtual machines immediately on any host. This is a significant advantage of virtualization during the COVID-19 pandemic, when students have to study remotely. Each student can have his or her own virtual laboratory;
- the ability to enhance control over backups, snapshots and recovery of virtual machines in case of failures.

References

[1] M. Pavlenko, L. Pavlenko, Formation of communication and teamwork skills of future IT-specialists using project technology, Journal of Physics: Conference Series 1840 (2021) 012031. doi:10.1088/1742-6596/1840/1/012031.

[2] V. H. Khomenko, L. V. Pavlenko, M. P. Pavlenko, S. V. Khomenko, Cloud technologies in informational and methodological support of university students' independent study, Information Technologies and Learning Tools 77 (2020) 223–239. URL: https://journal.iitta.gov.ua/index.php/itlt/article/view/2941. doi:10.33407/itlt.v77i3.2941.

[3] D. L. Lunsford, Virtualization Technologies in Information Systems Education, Journal of Information Systems Education 20 (2009) 339. URL: http://jise.org/Volume20/n3/JISEv20n3p339.html.

[4] V. V. Osadchyi, N. V. Valko, N. O. Kushnir, Design of the educational environment for STEM-oriented learning, Information Technologies and Learning Tools 75 (2020) 316–330.

[5] S. Ray, S. Srivastava, Virtualization of science education: a lesson from the COVID-19 pandemic, Journal of Proteins and Proteomics (2020) 1–4. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7261257/. doi:10.1007/s42485-020-00038-7.

[6] G. Stefanek, The use of virtualization technology to support information technology programming courses, Issues in Information Systems 18 (2017).

[7] L. Yan, Development and application of desktop virtualization technology, in: 2011 IEEE 3rd International Conference on Communication Software and Networks, IEEE, 2011, pp. 326–329.
[8] D. Yuan, B. Cross, Evaluating and using cloud computing for online hands-on learning, Journal of Computing Sciences in Colleges 29 (2014) 191–198.
[9] D. Yuan, C. Lewandowski, J. Zhong, Developing a Private Cloud Based IP Telephony Laboratory and Curriculum, Cloud Computing for Teaching and Learning: Strategies for Design and Implementation: Strategies for Design and Implementation (2012) 126.
[10] J. Chamberlin, J. Hussey, B. Klimkowski, W. Moody, C. Morrell, The Impact of Virtualized Technology on Undergraduate Computer Networking Education, in: Proceedings of the 18th Annual Conference on Information Technology Education, SIGITE '17, Association for Computing Machinery, New York, NY, USA, 2017, pp. 109–114. doi:10.1145/3125659.3125693.
[11] M. Barrionuevo, C. Gil, M. Giribaldi, C. Suarez, C. Taffernaberry, Virtualization in Education: Portable Network Laboratory, in: A. E. De Giusti (Ed.), Computer Science – CACIC 2017, volume 790, Springer International Publishing, Cham, 2018, pp. 90–98. URL: http://link.springer.com/10.1007/978-3-319-75214-3_9. doi:10.1007/978-3-319-75214-3_9.
[12] V. Oleksiuk, O. Oleksiuk, The practice of developing the academic cloud using the Proxmox VE platform, Educational Technology Quarterly 2021 (2021) 605–616. doi:10.55056/etq.36.
[13] M. Popel, S. V. Shokalyuk, M. Shyshkina, The Learning Technique of the SageMathCloud Use for Students Collaboration Support, in: V. Ermolayev, N. Bassiliades, H. Fill, V. Yakovyna, H. C. Mayr, V. S. Kharchenko, V. S. Peschanenko, M. Shyshkina, M. S. Nikitchenko, A. Spivakovsky (Eds.), Proceedings of the 13th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer, ICTERI 2017, Kyiv, Ukraine, May 15-18, 2017, volume 1844 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2017, pp. 327–339. URL: https://ceur-ws.org/Vol-1844/10000327.pdf.
[14] P. Segeč, M. Moravčík, M. Kontšek, J. Papán, J. Uramová, O. Yeremenko, Network virtualization tools – analysis and application in higher education, in: 2019 17th International Conference on Emerging eLearning Technologies and Applications (ICETA), 2019, pp. 699–708. doi:10.1109/ICETA48886.2019.9040148.
[15] Z. Seidametova, Z. Abduramanov, G. Seydametov, Hackathons in computer science education: monitoring and evaluation of programming projects, Educational Technology Quarterly 2022 (2022) 20–34. doi:10.55056/etq.5.
[16] J. Soler, Virtualization-support cases in engineering education, in: 2011 3rd International Congress on Engineering Education (ICEED), IEEE, 2011, pp. 1–3.
[17] T. Vakaliuk, Structural model of a cloud-based learning environment for bachelors in software engineering, Educational Technology Quarterly 2021 (2021) 257–273. doi:10.55056/etq.17.
[18] T. Vakaliuk, O. Spirin, V. Kontsedailo, Formation of digital competence of CS bachelors in the use of cloud-based learning environments, Educational Technology Quarterly 2021 (2021) 388–401. doi:10.55056/etq.26.
[19] K. Vlasenko, O. Chumak, D. Bobyliev, I. Lovianova, I. Sitak, Development of an Online-Course Syllabus "Operations Research Oriented to Cloud Computing in the CoCalc System", in: A. Bollin, H. C. Mayr, A. Spivakovsky, M. V. Tkachuk, V. Yakovyna, A. Yerokhin, G. Zholtkevych (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume I: Main Conference, Kharkiv, Ukraine, October 06-10, 2020, volume 2740 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 278–291. URL: https://ceur-ws.org/Vol-2740/20200278.pdf.
[20] D. Yuan, L. Cody, J. Zhong, Developing IP telephony laboratory and curriculum with private cloud computing, in: Proceedings of the 2011 conference on Information technology education, 2011, pp. 107–112.
[21] D. Yuan, C. Lewandowski, B. Cross, Building a green unified computing IT laboratory through virtualization, Journal of Computing Sciences in Colleges 28 (2013) 76–83.
[22] S. Abubakr, F. Hussein, P. Sarfo, Implementation of an IP Telephony System Based on Asterisk PBX; A Case Study of Garden City University College, Ghana, International Journal of Computer

Applications 177 (2019) 14–20. URL: http://www.ijcaonline.org/archives/volume177/number28/muntaka-2019-ijca-919743.pdf. doi:10.5120/ijca2019919743.

[23] S. Kaul, A. Jain, Study on the Future of Enterprise Communication by Cloud Session Border Controllers (SBC), in: G. Singh Tomar, N. S. Chaudhari, J. L. V. Barbosa, M. K. Aghwariya (Eds.), International Conference on Intelligent Computing and Smart Communication 2019, Algorithms for Intelligent Systems, Springer, Singapore, 2020, pp. 407–414. doi:10.1007/978-981-15-0633-8_39.

[24] M. Moravcik, M. Kontsek, Proposal of VoIP infrastructure and services for academia - case study, in: 2019 17th International Conference on Emerging eLearning Technologies and Applications (ICETA), 2019, pp. 540–545. doi:10.1109/ICETA48886.2019.9040092.

[25] J. Rendon Schneir, T. Plückebaum, VoIP network architectures and impacts on costing, info 12 (2010) 59–72. doi:10.1108/14636691011040486.

[26] I. Setiawan, A. W. W. Nugraha, A. S. P. Atmaja, Unjuk Kerja IP PBX Asterisk dan FreeSWITCH pada Topologi Bertingkat di Jaringan Kampus, JURNAL INFOTEL 9 (2017) 231–240. URL: https://ejournal.st3telkom.ac.id/index.php/infotel/article/view/217. doi:10.20895/infotel.v9i3.217.

[27] O. V. Prokhorov, V. O. Lisovichenko, M. S. Mazorchuk, O. H. Kuzminska, Implementation of digital technology for student involvement based on a 3D quest game for career guidance and assessing students' digital competences, Educational Technology Quarterly 2022 (2022) 366–387. doi:10.55056/etq.430.

[28] S. Semerikov, A. Striuk, L. Striuk, M. Striuk, H. Shalatska, Sustainability in Software Engineering Education: A case of general professional competencies, E3S Web of Conferences 166 (2020). doi:10.1051/e3sconf/202016610036.

[29] A. M. Striuk, S. O. Semerikov, H. M. Shalatska, V. P. Holiver, Software requirements engineering training: problematic questions, CEUR Workshop Proceedings 3077 (2022) 3–11.

[30] A. M. Striuk, S. O. Semerikov, Professional competencies of future software engineers in the software design: teaching techniques, Journal of Physics: Conference Series 2288 (2022) 012012. doi:10.1088/1742-6596/2288/1/012012.

[31] T. A. Vakaliuk, V. Kontsedailo, D. Antoniuk, O. Korotun, S. Semerikov, I. S. Mintii, Using Game Dev Tycoon to Create Professional Soft Competencies for Future Engineers-Programmers, in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 808–822. URL: https://ceur-ws.org/Vol-2732/20200808.pdf.

[32] K. Vlasenko, O. Chumak, I. Sitak, O. Chashechnikova, I. Lovianova, Developing informatics competencies of computer sciences students while teaching differential equations, Espacios 40 (2019).

[33] Drews, J. E., Going Virtual, Network Computing 19 (2006) 5.

[34] K. Barr, P. Bungale, S. Deasy, V. Gyuris, P. Hung, C. Newell, H. Tuch, B. Zoppis, The VMware mobile virtualization platform: is that a hypervisor in your pocket?, ACM SIGOPS Operating Systems Review 44 (2010) 124–135.

[35] S. Han, H.-W. Jin, Full virtualization based ARINC 653 partitioning, in: 2011 IEEE/AIAA 30th Digital Avionics Systems Conference, IEEE, 2011, pp. 7E1–1.

[36] S. A. Babu, M. J. Hareesh, J. P. Martin, S. Cherian, Y. Sastri, System Performance Evaluation of Para Virtualization, Container Virtualization, and Full Virtualization Using Xen, OpenVZ, and XenServer, in: 2014 Fourth International Conference on Advances in Computing and Communications, 2014, pp. 247–250. doi:10.1109/ICACC.2014.66.

[37] P. Li, Centralized and decentralized lab approaches based on different virtualization models, Journal of Computing Sciences in Colleges 26 (2010) 263–269.

Integration of laboratory equipment in remote learning environments

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Abstract

This research examines the integration and implementation strategies for laboratory work within remote learning environments, alongside an analysis of virtual laboratories as an alternative to traditional practical training. We investigate the distinct challenges faced by higher education institutions in laboratory instruction during the COVID-19 pandemic, drawing upon international commission data. The study critically evaluates the advantages and limitations of remote laboratory execution, particularly focusing on the complexities of transitioning from physical to virtual experimentation. Through a detailed case study of a bioelectronics and biomechanics laboratory, we demonstrate the feasibility of remote laboratory access via Internet-based solutions. The research concludes by proposing strategic directions for the advancement of virtual practical work within the computer information technologies department, contributing to the broader discourse on the future of practical education in digital environments.

Keywords

technology-enhanced learning, remote laboratory instruction, virtual experimentation, computer-numerical control systems, additive manufacturing

1. Introduction

The digitalisation of higher education has been progressively advancing [1, 2], with institutions increasingly migrating educational materials and activities onto virtual learning platforms such as Moodle and Blackboard [3]. However, the unprecedented circumstances precipitated by the COVID-19 pandemic and ongoing Russian invasion of Ukraine have catalysed an extraordinary transformation in pedagogical approaches [4, 5], particularly in laboratory-based instruction. This paradigm shift has necessitated the rapid transition of traditional classroom environments to virtual spaces, facilitated by video conferencing platforms such as Zoom, Webex, and Microsoft Teams.

The Department of Computer Information Technologies at Donbas State Engineering Academy, like numerous institutions globally, faced the imperative to transition to remote learning modalities. However, a significant challenge emerged regarding the practical component of technical education – specifically, laboratory work requiring specialised equipment. This challenge is particularly acute in technical disciplines, where the development of professional competencies is inextricably linked to hands-on laboratory experience.

The integration of laboratory work within remote learning environments thus presents a critical pedagogical challenge that demands innovative solutions. The *aim* of this research is to investigate the feasibility and methodological approaches for conducting laboratory work in remote learning contexts, with particular emphasis on maintaining educational quality and practical skill development.

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2. Related work

Consideration of the specifics of conducting a laboratory workshop in a distance learning environment should begin with a consideration of the specifics of education in the context of the coronavirus pandemic in general. The pandemic, on a global scale, has affected not only all spheres of public life [6], but also each person individually, and not only on the physical but also on the psycho-emotional levels [7, 8]. This was especially acutely felt by the education sector since it required a total transfer of all educational activities to a distance mode. According to Executive Director of Chandigarh University (India) S. K. Tripath, "The new coronavirus has affected employment, education, energy, agriculture and other areas of the global economy, including the emotional state of citizens. Higher education institutions (HEIs), including universities, colleges and other institutions of higher education, are no exception" [9]. According to UNESCO, the COVID-19 pandemic has led to the largest disruption in education systems in history, affecting nearly 1.6 billion students in more than 190 countries and on all continents. School and other educational closures have affected 94% of the global student population, with 99% in low- and lower-middle-income countries [10]. According to the same UNESCO, 826 million students in the world do not have personal computers, 706 million (43%) do not have access to the Internet [11].

In high school, the use of web-based distance education is expanding rapidly [12]. This requires constant improvement of the technological and methodological support of the educational process. Failure in education is a serious threat to the entire society. Therefore, educational institutions must respond quickly and ensure the continuity of educational processes. Research is underway to develop technical, organizational, and pedagogical changes that educational institutions must implement to use different methods of interaction, ensure continuity and provide high-quality education [13].

Research on the advantages and disadvantages of distance education is important [14]. Many universities are researching to examine the effectiveness of distance learning at universities in light of the coronavirus pandemic and to identify the barriers that university students face [15]. Bataineh et al. [16] is pointed out that distance learning requires an exceptional environment, ability, and IT skills in addition to smart devices and applications that enable video conferencing. Another important area is the study of methods and means for involving students in the online learning process [17]. An important step in the transition to online of many laboratories that are used in higher education, especially in STEM fields [18, 19, 20, 21]. This is important for students of those specialties that require access to physical objects: devices, sensors, control devices. One of the ways to solve this problem is to use remote lab and virtual lab technologies when programming an embedded system and applying them to managing technical objects [22, 23, 24]. A virtual laboratory is a software and hardware complex that allows research without direct contact with real production or educational equipment, or in the absence of it [23, 25, 26]. The remote lab includes real technological equipment, software, and hardware for controlling the technological complex and analog-digital conversion of measuring signals from sensors installed on the equipment. At the same time, it should be ensured: the operation of the equipment, a reliable access channel via the Internet, access dispatching and accounting of work performed, video stream transmission using appropriate equipment, etc. These tasks are solved, for example, in the GOLDi system [27]. Within the GOLDi remote lab, interactive content objects can be offered to students to digitally support learning processes. These are digital, immersive tools that allow you to explore learned content with predefined or self-created examples. Virtual lab emulates laboratory equipment through the use of mathematical models [28, 29]. It is also necessary to improve the technologies of the educational process based on the use of IT.

To ensure a proper response to emerging problems, universities need to focus on changing not only teaching methods but also the very approaches to teaching, organizing the educational process, and to do this quality and quickly. On the other hand, it became necessary to abandon the traditional method of planning and implementing educational programs. A regulatory component of the educational process during a pandemic in the Donbas State Engineering Academy was the "Regulations on distance learning for applicants for higher education at the Donbas State Engineering Academy in special conditions" [30]. The implementation of this provision is based on the expansion of distance learning opportunities through the digitalization of education, which, on the one hand, requires an analysis of the digital infrastructure of the academy, and on the other, its management. This analysis led to the solution of a global problem for technical universities – how to implement a laboratory practice on special equipment in this mode.

All laboratory work can be classified according to the type of disciplines where they are used. This applies more to special disciplines, where the student is often given the task of measuring the characteristics of any process using real devices or maintaining the process occurring in a given state. It is also possible to set some target state, which should be achieved in the process of laboratory experiment by appropriate actions of the student [31].

3. Case study

Consider the possibilities and ways of remote use of laboratory equipment of laboratories of bioelectronics and biomechanics of the Department of Computer Information Technologies of Donbas State Engineering Academy. They are equipped with modern research and production equipment that was purchased as part of the work in the international project BioArt Erasmus+ and allows research on the use of modern computer information technology in electronics, mechanics, biomechanics, and mechatronics. The production equipment of the laboratories includes machines with computer numerical control (CNC) and a 3D printer. This equipment allows to significantly expand the experience of students in the field of computer modeling and automated design in such CAD-systems as AutoCAD (2D modeling) SolidWorks and PTC Creo (3D modeling) by moving from computer models of objects to their material embodiment.

Computer numerical control means a computerized control system that reads the instructions of a specialized programming language and controls the drives of metal, wood, and plastic machining machines and machine tools. The CNC system interpreter translates the program from the input language to the control commands of the main drive, feed drives, controllers of the machine units (enable / disable cooling, for example). To determine the required trajectory of the working body as a whole (tool/work piece) by the control program (CP) uses an interpolator that calculates the position of the intermediate points of the trajectory specified in the program end. CNC machining increases productivity and accuracy of operations, guarantees a constant level of quality, which in most cases far exceeds the quality of traditional manual machining. Many orders that previously had to be abandoned can now be fulfilled easily and effortlessly, which in the meantime is considered exclusive and is the category of the largest profit [32].

CNC machines are represented by the following models. CNC machine Krechet-4060 manufactured by the Ukrainian company "CNC machines" (figure 1). This machine can be used for 2D and 3D milling of all types of plastics, wood, plywood, MDF, foam, composite, and light metals. The working field of the machine 400 x 600 mm, stroke on the Z-axis 100 mm, processing error 0.08 mm.

Figure 1: CNC machine Krechet-4060.

These are the Sherline 5410 CNC drilling and milling machine and the Sherline 4410 CNC lathe (figure 2). Sherline is located in the United States and is widely known in the world for quality small machines. These machines allow you to perform machining of parts in both software and manual control mode. The free version of Mach 3 is used as software for controlling motor controllers. It is enough to control the processing of medium-sized parts.

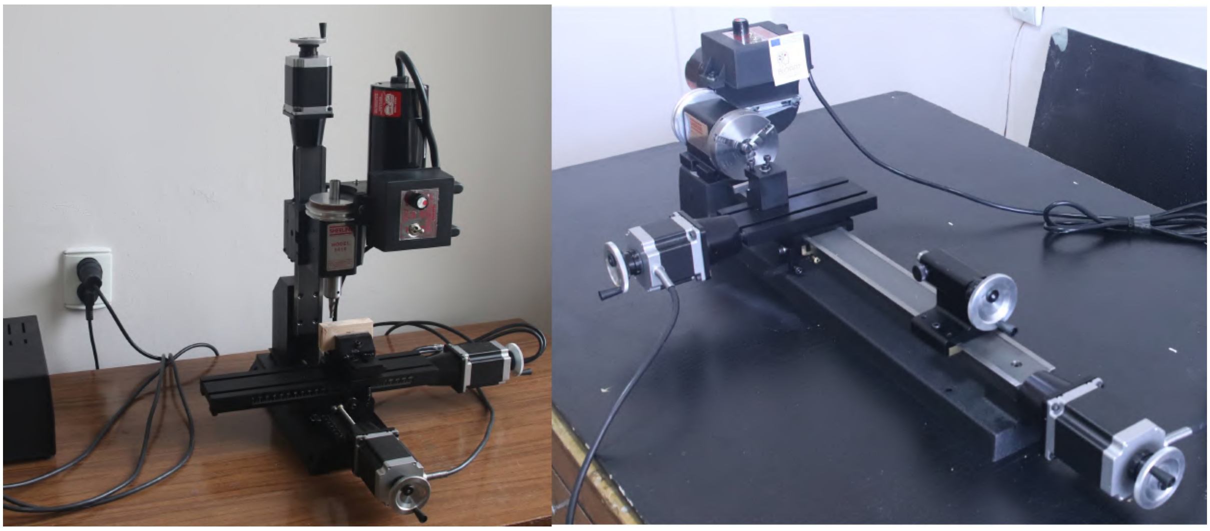

Figure 2: CNC machines: Sherline 5410 CNC and Sherline 4410 CNC.

The Sherline 5410 CNC drilling and milling machine have a motor power of 0.6 kW, a spindle speed range of 70–2800 rpm, axial movement: X/Y/Z – 220/127/159 mm, respectively. Stepper motors to control the movement of the axes with a capacity of 0.2 kW.

The Sherline 4410 CNC lathe has a motor power of 0.6 kW, spindle speed range 70–2800 rpm, spindle bore diameter 10 mm, rear headstock quill stroke 45 mm, rear headstock quill cone – MK1, turning diameter over frame 180 mm, turning diameter above the transverse caliper 90 mm, the distance between the centers 430 mm, the course of the transverse caliper 110 mm. Stepper motors to control the movement of the axes with a capacity of 0.2 kW. There is a complete set of equipment that allows you to process not completely cylindrical parts and cut threads. The machine allows to carry out processing with simultaneous movement of the tool on two coordinates.

Additive technologies have made a big qualitative leap in recent years, moving from the category of industrial equipment to personal devices. Due to this, there is an opportunity for the widespread introduction of this technology in the educational process. This allows not only to refine and expand the classic laboratory workshop but also to increase students' motivation and develop their competencies in the field of new technologies and their practical application.

In the conditions of active modernization of education, equipping universities with modern computer technology and transition to various forms of e-learning, there is an active introduction into the educational process of various virtual simulators and complexes designed to replace real physical experiment, the base of which is often not updated and obsolete over time. But a real physical experiment plays a very important role in the learning process. It allows not only to instill skills in working with equipment, but also to develop research and cognitive interest in students [33].

The presence of a large number of 3D printing technologies on the one hand gives a wide field for choice, on the other hand, imposes certain restrictions on their implementation. One of the most common 3D printing technologies is FDM (fused deposition modeling).

Among the main advantages of this type of printing are the following:

- the use of fairly compact printing devices that do not require special knowledge and skills in installation and operation;

- relatively low (compared to devices that use other technological processes) cost, both the devices themselves and consumables;
- the principle of the press is simple and technological that does not demand special places of installation;
- openness of technology, i.e. the possibility of its improvement and modification (the possibility of assembling a printing device from a ready-made designer or set of components).

Equipment for additive production in laboratories is represented by a 3D printer FARM2 (figure 3). This 3D printer has a printing area of 200x200x200 mm, implements ULTIMAKER kinematics, and has the ability to print the following types of plastic: PLA, ABS, PVA, Nylon, HDPE, PCL, PET-G.

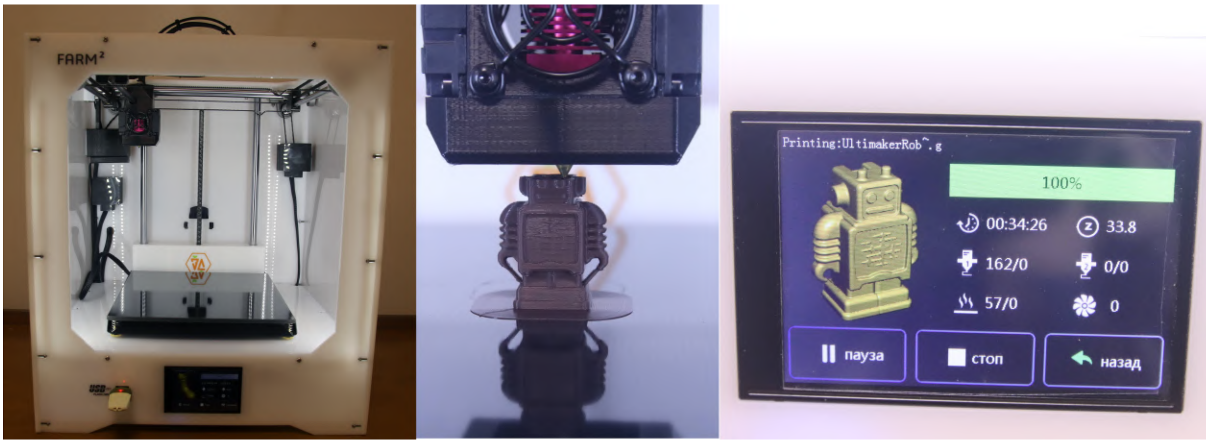

Figure 3: 3D printer FARM2.

Let's move directly to consider the possibility of remote laboratory work on CNC machines and 3D printers. Unfortunately, at the moment, for the full operation of machines and printers, some operations can only be performed by humans. For CNC machines it is the installation and replacement of working tools, blanks and finished products, chip cleaning. For 3D printers, this is a replacement for plastic and printed models. Although for some of these operations there is already a solution for full or partial automation (tool replacement and chip removal), laboratory work on CNC machines and 3D printers without the intervention of a teacher or laboratory assistant is currently impossible. But, despite this, it is already possible to remotely monitor the operation of CNC machines and 3D printers, get the parameters of their work and quickly adjust them. Consider ready-made solutions in this area.

In [34] the possibility of quality control and remote control of the device using a server is considered. The development of a server for CNC machine tool management is considered in order to improve the user experience and expand the capabilities of the device, including remote monitoring of the device. The work is based on the implementation of synchronous engine control using such parameters as: Constant snap period, Constant jerk period, Constant acceleration period, Constant velocity period, and imposed snap bound. This set of parameters is a classic for CNC machines. To control the device, it uses a simple built-in system (single-board computer) Beaglebone Black with control through the OS Linux kernel, acting as an operating system. Due to the choice of OS Linux as the operating system, the firmware software is open source.

To implement the firmware used a patch RTLinux [35], designed to work with components in real-time. The exchange of information between blocks in real-time is through shared memory. A program in C++ using a server on Linux was developed for remote device management. The program works as a server processing client requests. To implement the client part in the course of work were considered 3 options: a console application on Linux, a console application on Windows, and an application with a graphical interface. PRUSS firmware was developed to perform real-time calculations. The server application used writes data to the shared memory, which uses the PRUSS firmware to generate control signals and exchange their states via GPIO. The board and computer interact via a TCP connection via an Ethernet port.

One of the most common open-source firmware for remote control of 3D printers is the RepRap system. In [36] its application is considered. The web server is developed in Python in conjunction with the Tornado framework. The authors highlight some advantages of using the above framework to implement the server. The main advantage is the lightness of the system and the ability to scale to service up to tens of thousands of open connections, which is well suited for the operation of the printer management system during long-term use of the connection. The paper describes in detail the principle of client-server communication based on the HTTP protocol, which allows studying in detail the process of information transfer. The client part is a web page. As a result of firmware research, promising directions of technology development are proposed, including improving the functionality of the remote Rep-Rap server.

To improve the user experience when working with printing devices, the capabilities of 3D printers need to ensure their extensibility. One of these modifications is to provide full or partial tracking of the behavior of device modules. Monitoring the printing process requires access to readings from various types of sensors and printer components. Monitoring the printing process requires access to readings from various types of sensors and printer components. This system allows you to automate the collection of information about the device for subsequent display of data to the user to analyze the operation of the printer. There are also more advanced technologies for tracking the printing process, in which the status of the printer is monitored by analyzing readings from sensors and the position of the head using a neural network [37]. The article analyzes the operation of the position sensor, which is used to collect data on the status of the printer. It uses the prediction root mean square error as an indicator to describe the operating state of the printer. As a prospect for the development of technology, the introduction of such analysis into the remote control system of a 3D printer should be considered, it will allow monitoring the quality of the printing process and remotely monitoring the health of the device.

Also, many amateur projects for remote control of 3D printers on the use of open-source software (more often OctoPrint) and single-board computers Raspberry Pi and Orange Pi are posted in the public domain.

Consider the ways of remote use of equipment for research and development. The study of the mechanical properties of medical purposes, for example, metals, composites, threads, are investigated on a universal testing machine UIT STM 001, which can be completed with a variety of equipment and devices, and the software allows testing according to various standards (GOST, GB, ASTM, DIN, ISO, etc.) and techniques (figure 4). Using an application programming interface (API) allows you to develop software products to extend the capabilities of the testing machine.

Figure 4: Universal testing machine UIT STM 001.

Full automation of the testing machine has the same obstacles as the automation of machine tools and 3D printers - human intervention is required, in the case of a testing machine, to replace prototypes. The ways of partial remote translation of laboratory work on a testing machine are also similar – remote monitoring and control.

But in the case of a testing machine, an alternative way is possible – replacing real laboratory works with virtual ones [38, 39, 40]. In [28], a prototype of virtual laboratory work was developed for use in the educational process in the course “Resistance of materials”. The software package in real-time provides a full cycle of laboratory work: preparatory stage (training), installation and removal of the sample, performing measurements of the sample before and after testing, test, plotting a tensile diagram to determine the main mechanical strength characteristics (figure 5). The tests have shown that the use of modern technologies for performing virtual laboratory work in the educational process significantly increases the quality and efficiency of the learning process and can be used in conjunction with work on real equipment.

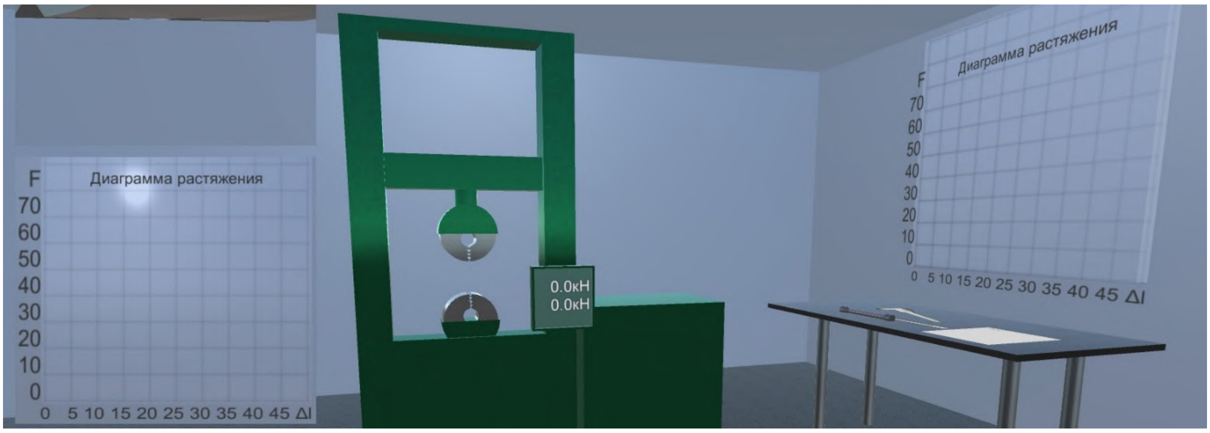

Figure 5: Program interface with three-dimensional models, interface, and mini cameras for simultaneous control of all processes [28].

Experience has shown that most students had no problems with running the labs and completing them. We believe that the best result is achieved when they are conducted in real-time, with the teacher’s explanations via video link and dialogue with the students.

4. Conclusion

Developed courses are at the stage of implementation in the educational process. The study of the features of laboratory work in the conditions of distance learning showed:

- at this point, it is impossible to make complete automation of equipment for remote laboratory work. Human intervention is required for some operations. This makes it relevant to develop communications between students, teachers, and laboratory assistants using modern electronic means of communication, planning, and optimization of the working time of laboratory equipment;
- there are many ready-made solutions for remote monitoring and control of laboratory equipment using open source software, single-board computers, cloud services, server, and client applications;
- in some cases, an alternative to laboratory work on real equipment is to replace them with virtual laboratory works.

The authors do not view the virtual labs as a complete substitute for the real ones. However, we think that they will organically complement classroom work after the pandemic and war are over.

References

[1] A. V. Morozov, T. A. Vakaliuk, I. A. Tolstoy, Y. O. Kubrak, M. G. Medvediev, Digitalization of thesis preparation life cycle: a case of Zhytomyr Polytechnic State University, in: T. A. Vakaliuk, V. V. Osadchyi, O. P. Pinchuk (Eds.), Proceedings of the 2nd Workshop on Digital Transformation of Education (DigiTransfEd 2023) co-located with 18th International Conference on ICT in Education, Research and Industrial Applications (ICTERI 2023), Ivano-Frankivsk, Ukraine, September 18-22, 2023, volume 3553 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 142–154. URL: https://ceur-ws.org/Vol-3553/paper14.pdf.

[2] O. V. Bondarenko, O. V. Hanchuk, O. V. Pakhomova, I. M. Varfolomyeyeva, Digitalization of geographic higher education: Problems and prospects, Journal of Physics: Conference Series 2611 (2023) 012015. doi:10.1088/1742-6596/2611/1/012015.

[3] L. Fadieieva, S. Semerikov, Exploring the Interplay of Moodle Tools and Student Learning Outcomes: A Composite-Based Structural Equation Modelling Approach, in: E. Faure, Y. Tryus, T. Vartiainen, O. Danchenko, M. Bondarenko, C. Bazilo, G. Zaspa (Eds.), Information Technology for Education, Science, and Technics, volume 222 of *Lecture Notes on Data Engineering and Communications Technologies*, Springer Nature Switzerland, Cham, 2024, pp. 418–435. doi:10.1007/978-3-031-71804-5_28.

[4] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, V. N. Soloviev, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, V. R. Ruban, Mask and Emotion: Computer Vision in the Age of COVID-19, in: Digital Humanities Workshop, DHW 2021, Association for Computing Machinery, New York, NY, USA, 2022, p. 103–124. doi:10.1145/3526242.3526263.

[5] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, S. O. Didkivska, Challenges facing distance learning during martial law: results of a survey of Ukrainian students, Educational Technology Quarterly 2023 (2023) 401–421. doi:10.55056/etq.637.

[6] S. Semerikov, S. Chukharev, S. Sakhno, A. Striuk, V. Osadchyi, V. Solovieva, T. Vakaliuk, P. Nechypurenko, O. Bondarenko, H. Danylchuk, Our sustainable coronavirus future, E3S Web of Conferences 166 (2020) 00001. doi:10.1051/e3sconf/202016600001.

[7] M. Velykodna, Psychoanalysis during the COVID-19 pandemic: Several reflections on countertransference, Psychodynamic Practice 27 (2021) 10–28. doi:10.1080/14753634.2020.1863251.

[8] M. Velykodna, I. Frankova, Psychological support and psychotherapy during the COVID-19 outbreak: First response of practitioners, Journal of Intellectual Disability - Diagnosis and Treatment 9 (2021) 148–161. doi:10.6000/2292-2598.2021.09.02.1.

[9] COVID-19 i Vysshee obrazovanie: Otuchitsia ot prezhnikh navykov radi sozdaniia sistemy obrazovaniia na budushchee (COVID-19 and Higher Education: Unlearn Previous Skills to Build Education for the Future), 2020. URL: https://www.un.org/ru/85374.

[10] International Commission on the Futures of Education, Education in a post-COVID world: Nine ideas for public action, United Nations Educational, Scientific and Cultural Organization, Paris, 2020. URL: https://unesdoc.unesco.org/ark:/48223/pf0000373717/PDF/373717eng.pdf.multi.

[11] R. Faek, T. A. El-Galil, The shift to online education in the arab world is intensifying inequality, 2020. URL: https://www.al-fanarmedia.org/2020/04/the-shift-to-online-education-in-the-arab-world-is-intensifying-inequality/.

[12] I. S. Mintii, T. A. Vakaliuk, S. M. Ivanova, O. A. Chernysh, S. M. Hryshchenko, S. O. Semerikov, Current state and prospects of distance learning development in Ukraine, CEUR Workshop Proceedings 2898 (2021) 41–55. URL: http://ceur-ws.org/Vol-2898/paper01.pdf.

[13] Ž. Bojović, P. D. Bojović, D. Vujošević, J. Šuh, Education in times of crisis: Rapid transition to distance learning, Computer Applications in Engineering Education 28 (2020) 1467–1489. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/cae.22318. doi:10.1002/cae.22318.

[14] Advantages and disadvantages of distance learning, 2017. URL: https://www.eztalks.com/elearning/advantages-and-disadvantages-of-distance-learning.html.

[15] D. Y. Bobyliev, E. V. Vihrova, Problems and prospects of distance learning in teaching fundamental subjects to future mathematics teachers, Journal of Physics: Conference Series 1840 (2021) 012002.

doi:10.1088/1742-6596/1840/1/012002.

[16] K. B. Bataineh, M. S. Atoum, L. A. Alsmadi, M. Shikhali, A silver lining of coronavirus: Jordanian universities turn to distance education, International Journal of Information and Communication Technology Education 17 (2021) 138–148. URL: https://www.igi-global.com/gateway/article/260754. doi:10.4018/IJICTE.20210401.oa1.

[17] Z. Chen, J. Jiao, K. Hu, Formative assessment as an online instruction intervention: Student engagement, outcomes, and perceptions, International Journal of Distance Education Technologies 19 (2021) 50–65. URL: https://www.igi-global.com/gateway/article/264397. doi:10.4018/IJDET.20210101.oa1.

[18] S. O. Semerikov, M. M. Mintii, I. S. Mintii, Review of the course "Development of Virtual and Augmented Reality Software" for STEM teachers: implementation results and improvement potentials, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 159–177. URL: https://ceur-ws.org/Vol-2898/paper09.pdf.

[19] R. P. Kukharchuk, T. A. Vakaliuk, O. V. Zaika, A. V. Riabko, M. G. Medvediev, Implementation of STEM learning technology in the process of calibrating an NTC thermistor and developing an electronic thermometer based on it, in: S. Papadakis (Ed.), Joint Proceedings of the 10th Illia O. Teplytskyi Workshop on Computer Simulation in Education, and Workshop on Cloud-based Smart Technologies for Open Education (CoSinEi and CSTOE 2022) co-located with ACNS Conference on Cloud and Immersive Technologies in Education (CITEd 2022), Kyiv, Ukraine, December 22, 2022, volume 3358 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 39–52. URL: https://ceur-ws.org/Vol-3358/paper25.pdf.

[20] M. M. Mintii, N. M. Sharmanova, A. O. Mankuta, O. S. Palchevska, S. O. Semerikov, Selection of pedagogical conditions for training STEM teachers to use augmented reality technologies in their work, Journal of Physics: Conference Series 2611 (2023) 012022. doi:10.1088/1742-6596/2611/1/012022.

[21] M. M. Mintii, STEM education and personnel training: Systematic review, Journal of Physics: Conference Series 2611 (2023) 012025. doi:10.1088/1742-6596/2611/1/012025.

[22] J. G. Zubía, G. R. Alves (Eds.), Using Remote Labs in Education: Two Little Ducks in Remote Experimentation, University of Deusto, Bilbao, 2011. URL: http://www.deusto-publicaciones.es/deusto/pdfs/otraspub/otraspub01.pdf.

[23] E. Sancristobal, S. Martín, R. Gil, P. Orduña, M. Tawfik, A. Pesquera, G. Diaz, A. Colmenar, J. García-Zubia, M. Castro, State of art, initiatives and new challenges for virtual and remote labs, in: 2012 IEEE 12th International Conference on Advanced Learning Technologies, 2012, pp. 714–715. doi:10.1109/ICALT.2012.232.

[24] O. Tsvetkova, O. Piatykop, A. Dzherenova, O. Pronina, T. A. Vakaliuk, I. Fedosova, Development and implementation of virtual physics laboratory simulations for enhanced learning experience in higher education, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 98–110. URL: https://ceur-ws.org/Vol-3679/paper10.pdf.

[25] S. Malchenko, From smartphones to stargazing: the impact of mobile-enhanced learning on astronomy education, Science Education Quarterly 1 (2024) 1–7. doi:10.55056/seq.816.

[26] D. A. Karnishyna, T. V. Selivanova, P. P. Nechypurenko, T. V. Starova, S. O. Semerikov, Enhancing high school students' understanding of molecular geometry with augmented reality, Science Education Quarterly 1 (2024) 25–40. doi:10.55056/seq.818.

[27] GOLDi : The Grid of Online Laboratory Devices Ilmenau, 2021. URL: http://goldi-labs.net/.

[28] L. V. Vasilyeva, A. S. Portnyagin, Implementation of a simulator of a specialized explosive machine for conducting virtual laboratory work, Scientific papers of Donetsk National Technical University: Informatics, Cybernetics and Computer Science 24 (2017) 30–35. URL: http://nbuv.gov.ua/UJRN/Npdntu_inf_2017_1_6.

[29] O. Tarasov, L. Vasylieva, O. Altukhov, V. Anosov, Automation of the synthesis of new design

solutions based on the requirements for the functionality of the created object, CEUR Workshop Proceedings 2711 (2020) 161–175. URL: http://ceur-ws.org/Vol-2711/paper13.pdf.

[30] Polozhennia pro dystantsiine navchannia zdobuvachiv vyshchoi osvity za dennoiu formoiu u donbaskii derzhavnii mashynobudivnii akademii v osoblyvykh umovakh, 2020. URL: http://www.dgma.donetsk.ua/docs/acts/%D0%9F%D0%BE%D0%BB%D0%BE%D0%B6%D0%B5%D0%BD%D0%BD%D1%8F_%D0%BF%D1%80%D0%BE_%D0%94%D0%B8%D1%81%D1%82%D0%B0%D0%BD%D1%86_%D0%BD%D0%B0%D0%B2%D1%87_%D0%B2_%D0%BA%D0%B0%D1%80%D0%B0%D0%BD%D1%82%D0%B8%D0%BD.pdf.

[31] A. F. Tarasov, I. A. Getman, S. S. Turlakova, I. I. Stashkevych, S. M. Kozmenko, Methodical aspects of preparation of educational content on the basis of distance education platforms, CEUR Workshop Proceedings 2643 (2020) 161–173. URL: http://ceur-ws.org/Vol-2643/paper08.pdf.

[32] D. Y. Mikhieienko, Introduction of the use of cnc machine in teaching the discipline of computer design technology, in: Automation and computer-integrated technologies in production and education: state, achievements, development prospects, Cherkasy, 2020, pp. 263–264. URL: https://conference.ikto.net/pub/akit_2020_16-22march.pdf.

[33] D. Mikhieienko, The use of additive technologies in the educational process of the department of computer information technologies, in: Modern education - accessibility, quality, recognition, DSEA, Kramatorsk, 2020, pp. 109–111.

[34] P. Rocha, E. Tostes, Development of an embedded CNC control system, in: 2018 13th IEEE International Conference on Industry Applications (INDUSCON), 2018, pp. 407–412. doi:10.1109/INDUSCON.2018.8627296.

[35] B. Savant, R. Desai, Deployment of RTLinux on various platforms, in: 2007 IET-UK International Conference on Information and Communication Technology in Electrical Sciences (ICTES 2007), 2007, pp. 1058–1062.

[36] C. Liu, P. Jiang, W. Jiang, Embedded-web-based remote control for RepRap-based open-source 3D printers, in: IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, 2017, pp. 3384–3389. doi:10.1109/IECON.2017.8216573.

[37] S. Zhang, Z. Sun, J. Long, C. Li, Y. Bai, Dynamic condition monitoring for 3D printers by using error fusion of multiple sparse auto-encoders, Computers in Industry 105 (2019) 164–176. doi:10.1016/j.compind.2018.12.004.

[38] A. E. Kiv, O. Merzlykin, Y. O. Modlo, P. P. Nechypurenko, I. Y. Topolova, The overview of software for computer simulations in profile physics learning, CEUR Workshop Proceedings 2433 (2019) 352–362.

[39] P. Nechypurenko, T. Selivanova, M. Chernova, Using the cloud-oriented virtual chemical laboratory VLab in teaching the solution of experimental problems in chemistry of 9th grade students, CEUR Workshop Proceedings 2393 (2019) 968–983.

[40] P. Nechypurenko, O. Evangelist, T. Selivanova, Y. O. Modlo, Virtual chemical laboratories as a tools of supporting the learning research activity of students in chemistry while studying the topic "Solutions", CEUR Workshop Proceedings 2732 (2020) 984–995.

Developing pre-service teachers' digital competence through informatics disciplines in teacher education programs

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Abstract

This study investigated the effectiveness of the proposed didactic conditions and structural-functional model for developing pre-service teachers' digital competence through informatics disciplines. The positive dynamics observed in the experimental group's digital competence levels, particularly in the cognitive-informational and motivational-value components, contribute to growing research advocating for the systematic development of digital competence within teacher education programs. The findings underscore the importance of adopting a holistic, integrated approach to informatics disciplines, combining technical skills, pedagogical knowledge, and practical application through authentic, project-based learning experiences.

Keywords

digital competence, pre-service teachers, teacher education, informatics disciplines, pedagogical experiment

1. Introduction

The rapid digitalisation of society and education has highlighted the need for educators to possess a high level of digital competence to effectively integrate digital technologies into their professional practice [1, 2, 3, 4]. As defined by the European Commission's DigComp framework, digital competence involves the confident, critical, and responsible use of digital technologies for learning, work, and participation in society [5]. For teachers, this encompasses the ability to use digital tools to enhance teaching and learning, foster students' digital literacy, and promote innovative educational practices [6].

However, studies have revealed that pre-service teachers often lack sufficient digital competence, despite exposure to various informatics disciplines during their teacher education programs [7, 2]. This suggests that existing informatics courses do not adequately contribute to the full and targeted development of pre-service teachers' digital competence, necessitating a more intentional and systematic approach [8]. Recent years have necessitated reflection on the content and modalities of digital competence formation in pre-service teachers [9].

To address this issue, a structural-functional model was developed, incorporating specific didactic conditions that aim to foster digital competence development in pre-service teachers through the study of informatics disciplines. These conditions include:

1. Motivational conditionality of subjects' interaction in the digital learning environment.
2. Structuring of educational information in problematic, heuristic and integrative learning. models and its translation into project activities
3. Ensuring a systematic, complicating nature of students' learning activities with diagnostics and timely correction of outcomes using modern ICT.

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This study's purpose was to test the effectiveness of the proposed didactic conditions and structural-functional model in developing pre-service teachers' digital competence through a pedagogical experiment. The findings contribute to the growing body of research on digital competence development in teacher education and provide insights into effective strategies for preparing future teachers to integrate digital technologies into their professional practice.

2. Theoretical background

2.1. Digital competence in teacher education

The importance of developing pre-service teachers' digital competence has been increasingly recognized, as evidenced by the inclusion of digital competence frameworks in teacher education policies and curricula worldwide [10, 11]. The European Framework for the Digital Competence of Educators (DigCompEdu) outlines six areas of digital competence for teachers: professional engagement, digital resources, teaching and learning, assessment, empowering learners, and facilitating learners' digital competence [6].

Research has shown that pre-service teachers' digital competence is influenced by various factors, such as their personal experiences with technology, self-efficacy beliefs, and the quality of technology integration in their teacher education programs [12, 13]. Studies have also highlighted the need for teacher education programs to provide authentic, meaningful opportunities for pre-service teachers to develop their digital competence through hands-on practice, reflection, and peer collaboration [10, 11]. Digital competence is a vital combination of knowledge, abilities, and attitudes required for effective and responsible use of digital tools and technologies in the modern world [14].

2.2. Informatics disciplines in teacher education

Informatics (computer science) disciplines, such as programming, and information technology, play a crucial role in developing pre-service teachers' digital competence [2]. These disciplines provide students with the foundational knowledge and skills necessary to understand and use digital technologies effectively in educational contexts. However, research has shown that the existing informatics courses in teacher education programs often focus narrowly on technical skills and fail to adequately address the pedagogical aspects of technology integration [7, 2].

To better support pre-service teachers' digital competence development, informatics disciplines in teacher education need to adopt a more holistic, integrated approach that combines technical skills with pedagogical knowledge and practical application [10]. This can be achieved through authentic, problem-based learning activities, collaborative projects, and reflective practice [13, 12]. Additionally, informatics courses should be closely aligned with the broader teacher education curriculum and provide opportunities for pre-service teachers to apply their digital competence in real-world educational settings [11]. Training programs have been carried out to support digital competence, and it is important to examine how pre-service teachers plan to use the knowledge and skills gained from digital competence training in different contexts [15].

3. Methodology

3.1. Research design

A pedagogical experiment was conducted to test the effectiveness of the proposed didactic conditions and structural-functional model for developing pre-service teachers' digital competence through informatics disciplines. The experiment followed a quasi-experimental design, with a control group and an experimental group of pre-service teachers from two Ukrainian pedagogical universities.

The control group (n=93) studied according to traditional informatics discipline programs, while the experimental group (n=95) followed an experimental program that implemented the proposed didactic conditions and structural-functional model. The experiment was conducted over four academic years, from 2016 to 2020.

3.2. Participants

The study participants were 188 pre-service teachers enrolled in pedagogical specialties at two Ukrainian pedagogical universities. The control group consisted of 93 students (71% female, 29% male), while the experimental group comprised 95 students (69% female, 31% male). The participants' ages ranged from 18 to 23, with a mean age of 20.2 years (σ=1.4).

All participants were enrolled in informatics disciplines as part of their teacher education programs, which included courses such as computer science, programming, and information technology. The participants' prior experience with digital technologies varied, but all had basic computer literacy skills.

3.3. Instruments

Digital competence formation was assessed according to four structural-criterial components: motivational-value, cognitive-informational, operational-activity, and personal-reflexive. A range of diagnostic methods were employed to measure pre-service teachers' digital competence development:

- A series of tests were administered to assess participants' knowledge and understanding of digital technologies, computer science concepts, and pedagogical applications of technology.
- Participants completed questionnaires designed to gauge their attitudes, beliefs, and self-efficacy regarding the use of digital technologies in educational contexts.
- Semi-structured interviews were conducted with a subset of participants to gather more in-depth insights into their experiences, challenges, and growth in relation to digital competence development.
- Participants completed practical tasks and projects that required them to demonstrate their skills in using digital tools, creating digital content, and solving technology-related problems.
- Competency matrices were used to assess participants' performance in various aspects of digital competence, such as digital literacy, digital communication and collaboration, and digital content creation.
- Expert evaluations were conducted by university faculty and experienced teachers to assess participants' digital competence based on their performance in informatics disciplines and educational practice.
- Participants analyzed and discussed real-world case studies related to technology integration in education, allowing for the assessment of their critical thinking and problem-solving skills.
- Participants designed and implemented educational projects that demonstrated their ability to integrate digital technologies into teaching and learning activities.
- Participants maintained a reflective blog throughout the experiment, documenting their experiences, insights, and growth in relation to digital competence development.

These diverse diagnostic methods provided a comprehensive assessment of pre-service teachers' digital competence development throughout the pedagogical experiment.

3.4. Procedure

The pedagogical experiment was conducted in three stages: organizational, formative, and corrective. In the organizational stage, the experimental program was developed, incorporating the proposed didactic conditions and structural-functional model. The content of informatics disciplines was updated, and an author's electronic special course, "Digital Technologies in Education" (3 ECTS credits), was prepared. Diagnostic instruments were also developed and validated during this stage.

During the formative stage, the experimental group studied according to the experimental program, which implemented the three didactic conditions:

1. *Motivational conditionality of subjects' interaction in the digital learning environment*: This condition aimed to foster effective collaboration and co-creation among students and teachers in the digital learning environment. Problematic and developmental learning technologies, success situations, emotional stimulation, and gamified rating control were used to enhance students' motivation to master digital competence.
2. *Structuring of educational information in problematic, heuristic and integrative learning models and its translation into project activities*: This condition involved structuring educational information in problematic, heuristic, and integrative learning models and translating it into project activities. A technological scheme for forming digital competence was developed, serving as the basis for creating a system of learning tasks, contextual, game, and problem situations, web-quests, and case studies. These activities covered the motivational-value, cognitive-informational, operational-activity, and personal-reflexive aspects of students' activity in the virtual space.
3. *Ensuring a systematic, complicating nature of students' learning activities with diagnostics and timely correction of outcomes using modern ICT*: This condition involved introducing digital tools and technologies that optimized and intensified the learning of informatics disciplines. New ways of organizing training sessions, technological models of mobile, distance, and blended learning, game design, video and teleconferences, web forums, and workshops in synchronous and asynchronous modes were employed.

In the corrective stage, the results of the students' learning activities were monitored and corrected using both general (testing, questionnaires, interviews, control tasks) and specific methods (competency matrices, expert cards, case studies, educational projects, and blogs).

3.5. Data analysis

Quantitative data collected through tests, questionnaires, control tasks, and competency matrices were analyzed using descriptive and inferential statistics. Paired-sample t-tests were used to compare the pre-and post-experiment scores within each group, while independent-sample t-tests were employed to compare the experimental and control groups' post-experiment scores. Effect sizes (Cohen's d) were calculated to determine the magnitude of the differences between groups.

Qualitative data gathered through interviews, case studies, educational projects, and blog entries were analyzed using thematic analysis [16]. The data were coded and categorized into themes related to the four structural-criterial components of digital competence (motivational-value, cognitive-informational, operational-activity, and personal-reflexive). The themes were then compared and contrasted between the experimental and control groups to identify patterns and differences in digital competence development.

4. Results

4.1. Quantitative findings

The experimental group demonstrated positive, statistically significant dynamics in the levels of digital competence formation compared to the control group (table 1). The greatest development was observed in the cognitive-informational (+35.79%) and motivational-value (+25.26%) components of digital competence.

Paired-sample t-tests revealed significant improvements in the experimental group's digital competence scores from the initial to the final assessment across all four structural-criterial components (p<0.001). The effect sizes ranged from d=0.68 to d=1.24, indicating moderate to large effects.

Independent-sample t-tests showed that the experimental group's post-experiment scores were significantly higher than those of the control group in the cognitive-informational ($t(186)$=6.84, p<0.001, d=1.00) and motivational-value ($t(186)$=5.21, p<0.001, d=0.76) components. The differences in the operational-activity and personal-reflexive components were also significant but with smaller effect sizes (d=0.42 and d=0.51, respectively).

Table 1
Comparative dynamics of digital competence formation levels based on experiment results (%).

Levels	Experimental group		Control group	
	Initial	Final	Initial	Final
Initial	21.05	3.16	22.58	12.90
Average	34.74	26.32	34.41	33.33
Sufficient	26.32	43.16	24.73	33.33
High	17.89	27.37	18.28	20.43

4.2. Qualitative findings

The thematic analysis of interviews, case studies, educational projects, and blog entries revealed several key themes related to the development of digital competence in pre-service teachers:

- *Enhanced motivation and engagement*: participants in the experimental group reported increased motivation and engagement in learning informatics disciplines due to the interactive, project-based nature of the activities and the authentic use of digital tools.
- *Improved understanding of digital technologies*: experimental group participants demonstrated a deeper understanding of digital technologies, their applications in education, and the pedagogical implications of technology integration.
- *Increased confidence in using digital tools*: pre-service teachers in the experimental group expressed greater confidence in their ability to use digital tools for teaching and learning, as well as for personal and professional development.
- *Collaborative learning and peer support*: the experimental program fostered a strong sense of collaboration and peer support among pre-service teachers, facilitating the sharing of knowledge, skills, and experiences related to digital competence development.
- *Reflective practice and self-awareness*: participants in the experimental group demonstrated higher levels of reflective practice and self-awareness regarding their digital competence development, as evidenced by their blog entries and discussions during interviews.

These qualitative findings provide further evidence of the effectiveness of the proposed didactic conditions and structural-functional model in fostering digital competence development in pre-service teachers.

5. Discussion

The results of this pedagogical experiment confirm the effectiveness of the proposed didactic conditions and structural-functional model for developing pre-service teachers' digital competence through informatics disciplines. The positive dynamics observed in the experimental group's digital competence levels, particularly in the cognitive-informational and motivational-value components, align with recent research emphasizing the importance of intentional and systematic digital competence development in teacher education [12, 10, 11, 9].

The significant improvements in the experimental group's cognitive-informational component suggest that the problematic, heuristic, and integrative learning models, coupled with project-based activities, effectively facilitated the acquisition of knowledge and understanding related to digital technologies and their pedagogical applications. This finding supports the notion that informatics disciplines in teacher education should adopt a more holistic, integrated approach that combines technical skills with pedagogical knowledge and practical application [10, 13].

The substantial growth in the motivational-value component among experimental group participants highlights the importance of creating an engaging, collaborative digital learning environment that fosters motivation and positive attitudes towards technology integration. This finding aligns with research indicating that pre-service teachers' digital competence is influenced by their personal experiences, self-efficacy beliefs, and the quality of technology integration in their teacher education programs [12, 13].

The qualitative findings provide further insights into the factors contributing to the effectiveness of the experimental program. The enhanced motivation, improved understanding of digital technologies, increased confidence, collaborative learning, and reflective practice reported by experimental group participants underscore the value of authentic, meaningful learning experiences in developing digital competence [10, 11].

The substantial growth in the motivational-value component among experimental group participants highlights the importance of creating an engaging, collaborative digital learning environment that fosters motivation and positive attitudes towards technology integration. This finding aligns with research indicating that pre-service teachers' digital competence is influenced by their personal experiences, self-efficacy beliefs, and the quality of technology integration in their teacher education programs [12, 13]. It is crucial to examine how pre-service teachers plan to use the knowledge and skills gained from digital competence training in different contexts, such as personal, pedagogical, and professional digital competence [15].

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While the operational-activity and personal-reflexive components also showed significant improvements in the experimental group, the smaller effect sizes suggest that these aspects of digital competence may require additional attention and support. Future research could explore strategies for further enhancing pre-service teachers' practical skills and reflective capabilities in relation to digital competence development.

6. Conclusion

This pedagogical experiment provides evidence for the effectiveness of the proposed didactic conditions and structural-functional model in developing pre-service teachers' digital competence through informatics disciplines. The positive dynamics observed in the experimental group's digital competence levels, particularly in the cognitive-informational and motivational-value components, contribute to the growing body of research advocating for the systematic, intentional development of digital competence within teacher education programs.

The findings underscore the importance of adopting a holistic, integrated approach to informatics disciplines in teacher education, combining technical skills, pedagogical knowledge, and practical application through authentic, project-based learning experiences. The study also highlights the value of creating an engaging, collaborative digital learning environment that fosters motivation, confidence, and reflective practice among pre-service teachers.

The results of this experiment have several implications for teacher education policy and practice. First, teacher education programs should prioritize the intentional and systematic development of pre-service teachers' digital competence, recognizing its critical role in preparing future educators for the digitalized educational landscape. This may involve reforming existing informatics disciplines to better align with the holistic, integrated approach demonstrated in this study.

Second, teacher educators should adopt evidence-based strategies, such as the didactic conditions and structural-functional model proposed in this study, to effectively foster digital competence development in pre-service teachers. This may require professional development for teacher educators to enhance their own digital competence and pedagogical skills in integrating technology into their teaching practice.

Third, policymakers and educational institutions should invest in the necessary infrastructure, resources, and support systems to facilitate the effective integration of digital technologies in teacher education programs. This includes providing access to up-to-date digital tools, learning management systems, and online resources and offering technical and pedagogical support to both pre-service teachers and teacher educators.

Future research could explore the long-term impact of digital competence development interventions on pre-service teachers' technology integration practices during their induction phase and early career years. Longitudinal studies could provide valuable insights into the sustainability and transferability of the skills and knowledge acquired through such interventions.

Additionally, the proposed structural-functional model could be adapted and tested in different contexts and specializations within teacher education, such as primary education, secondary education, and subject-specific domains. Comparative studies could also investigate the effectiveness of different approaches to digital competence development in teacher education across various countries and educational systems.

References

[1] O. Ovcharuk, I. Ivaniuk, N. Soroko, O. Gritsenchuk, O. Kravchyna, The use of digital learning tools in the teachers' professional activities to ensure sustainable development and democratization of education in european countries, E3S Web of Conferences 166 (2021) 10019. doi:10.1051/e3sconf/202016610019.

[2] M. V. Moiseienko, N. V. Moiseienko, I. V. Kohut, A. E. Kiv, Digital competence of pedagogical university student: definition, structure and didactical conditions of formation, CTE Workshop Proceedings 7 (2020) 60–70. doi:10.55056/cte.310.

[3] O. Kuzminska, M. Mazorchuk, N. Morze, M. Prokopchuk, H. Danylchuk, Integrating digital competencies of researchers into Ph.D. curricula: a case study on open science education, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 195–208. URL: https://ceur-ws.org/Vol-3679/paper36.pdf.

[4] I. V. Lovianova, N. Y. Hrebin-Krushelnytska, R. Y. Kaluhin, A. V. Krasnoshchok, O. O. Kozhukhar, Formation of digital competence of specialists in socionomic professions as a pedagogical problem, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 209–223. URL: https://ceur-ws.org/Vol-3679/paper40.pdf.

[5] S. Carretero Gomez, R. Vuorikari, Y. Punie, DigComp 2.1: The Digital Competence Framework for Citizens with eight proficiency levels and examples of use, Publications Office of the European Union, Luxembourg, 2017. doi:10.2760/38842.

[6] C. Redecker, European Framework for the Digital Competence of Educators: DigCompEdu, Publications Office of the European Union, Luxembourg, 2017. doi:0.2760/159770.

[7] H. Heredia Ponce, M. F. Romero Oliva, E. Trigo Ibáñez, Towards digital competence from the conception of students in language instruction: A study within the master's degree in teaching in Andalusia, Journal of Technology and Science Education 14 (2024) 45–60. doi:10.3926/jotse.2375.

[8] N. S. Ponomareva, Role and place of Informatics in the training of future teachers of mathematics, Journal of Physics: Conference Series 1840 (2021) 012035. doi:10.1088/1742-6596/1840/1/012035.

[9] Ł. Tomczyk, Digital competence among pre-service teachers: A global perspective on curriculum change as viewed by experts from 33 countries, sEvaluation and Program Planning 105 (2024). doi:10.1016/j.evalprogplan.2024.102449.

[10] J. Tondeur, K. Aesaert, B. Pynoo, J. van Braak, N. Fraeyman, O. Erstad, Developing a validated instrument to measure preservice teachers' ICT competencies: Meeting the demands of the 21st century, British Journal of Educational Technology 48 (2017) 462–472. doi:10.1111/bjet.12380.

[11] L. Starkey, A review of research exploring teacher preparation for the digital age, Cambridge Journal of Education 50 (2020) 37–56. doi:10.1080/0305764X.2019.1625867.
[12] G. B. Gudmundsdottir, O. E. Hatlevik, “I just Google it” - Developing professional digital competence and preparing student teachers to exercise responsible ICT use, Nordic Journal of Comparative and International Education (NJCIE) 4 (2020) 39–55. doi:10.7577/njcie.3752.
[13] G. Falloon, From digital literacy to digital competence: the teacher digital competency (TDC) framework, Educational Technology Research and Development 68 (2020) 2449–2472. doi:10.1007/s11423-020-09767-4.
[14] J. Su, W. Yang, Digital competence in early childhood education: A systematic review, Education and Information Technologies 29 (2024) 4885–4933. doi:10.1007/s10639-023-11972-6.
[15] A. Çebi, C. Çolak, I. Reisoglu, T. B. Özdemir, Does Context Matter?: Examining Personal, Pedagogical, and Professional Digital Competencee, in: P. O. de Pablos, M. N. Almunawar, M. Anshari (Eds.), Developing Skills and Competencies for Digital and Green Transitions, IGI Global, Hershey, PA, 2023, pp. 1–28. doi:10.4018/978-1-6684-9089-1.ch001.
[16] V. Braun, V. Clarke, Using thematic analysis in psychology, Qualitative Research in Psychology 3 (2006) 77–101. doi:10.1191/1478088706qp063oa.

Implementing business simulation games for strategic management training of educational leaders in Ukraine

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Abstract

With the adoption of the new Law of Ukraine "On Education" in 2017, Ukrainian schools have gained greater autonomy in academic, organizational, financial, and personnel matters. This shift necessitates new approaches to training school principals and directors in strategic management. This paper examines the use of business simulation games as an innovative tool for developing the economic and managerial competencies of educational leaders. Drawing on a case study of trainings conducted in Ukraine from 2016-2021, we analyze the perceptions and learning outcomes of over 1,200 participants from preschool, secondary, vocational, and higher education institutions. The findings highlight the effectiveness of business simulations in providing immersive, experiential learning and bridging the gap between educational and business spheres. However, challenges related to participants' mindsets, skills, and institutional constraints are also identified. The paper concludes with recommendations for designing and implementing simulation-based trainings that are tailored to the needs of educational leaders in the context of ongoing reforms in Ukraine.

Keywords

business simulation games, educational leadership, strategic management training, experiential learning, education reform in Ukraine

1. Introduction

In modern conditions of transformation in Ukraine there was a need to reform the management of schools. The adoption of the Law of Ukraine "On Education" in 2017 launched mechanisms for structural reform of the management system and methods of carrying out the activities of schools. The Law stipulates that "the state guarantees the academic, organizational, financial and personnel autonomy of schools. The scope of autonomy of schools is determined by the Law, special laws and constituent documents of the school" [1]. We need special trainings programs for semi-directors and directors of schools, colleges and universities. Also there are introduced business instruments into everyday and strategic activity of educational organisations. During the trainings we conducted research in the format of a survey on three questions: 1) who is the client; 2) which is a product of the educational institution; 3) which is a raw material. And also we identified the main areas of training of principals of school using business-simulation.

At the article we described:

- peculiarity of new conditions for economic and managerial training of principals;
- mental and professional features of perception of business education;
- modern instruments of forming of economic and managerial competencies during training of principals of schools;

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2. New conditions for economic and managerial training of principals

Based on this, schools of all levels become full-fledged business entities with different forms of ownership and in different statuses (budgetary institution, non-profit school, profitable school). And the main type of their activity is educational [1]. In this regard, the introduction of economic and management approaches in the activities of schools becomes extremely important.

A sharp change in the role of the head of the school, the need to make a wide range of management decisions make not only to the established pedagogical norms of the school, but also to the traditional tools of business management. Given that the educational and business spheres of operation are quite distant and little intersect, one of the tasks of economists and scientists-educators is to approximate, adapt and implement economic tools of management and analysis in the daily activities of the school.

It is worth recalling the basic legislative changes that operate in the light of the current Law of Ukraine "On Education" in accordance with the levels of education Analyzing the legislative changes in the Laws of Ukraine "On Professional Higher Education" [2, 3], "On Complete General Secondary Education" [4] it is worth noting the following innovations:

- independence in certain forms of education, forms of organization of the educational process;
- the right to form and approve one's own staff list, respectively, free employment and dismissal of pedagogical, scientific-pedagogical and other employees;
- independence in financial, economic and other activities in accordance with the legislation and constituent documents;
- free disposal of own revenues;
- the head of the school directly manages the activities of his institution, he is a representative in external relations with state bodies, local governments, legal entities and individuals;
- the head decides the financial and economic activities of the school, forms its structure, forms and approves the staff list in accordance with the law, is the manager of property and funds, ensures compliance with staff and financial discipline;
- the head ensures the development and is responsible for the implementation of the approved development strategy of the school;
- the head is responsible for the results of the institution of professional higher education before the founder (founders) or his authorized body (persons).

A balancing role in the system of strategic management of a school is played by the pedagogical council of the school [4]:

- determination of strategy and perspective directions of development of school;
- considers the draft constituent document of the school, as well as proposals for amendments to it;
- considers the draft estimate (financial plan) of the institution and the annual financial report of the school, and other significant strategic steps.

Analyzing such changes in the adopted profile laws, which correspond to the Law of Ukraine "On Education", we can predict that in the new version of the law on vocational (technical) education in terms of powers of the institution, its head and collegial body will be written similar provisions. These steps lead to one thing – the need for radical change in the training and retraining of managers in the education system.

The offered article considers ways and ways of economic, administrative preparation of heads of schools and their deputies in the conditions of reforming of education.

3. Mental and professional features of perception of business education

In Ukraine during 2016-2021, research and experimental work of the all-Ukrainian level on the topic: "Development of business education in Ukraine as an element of state policy to promote entrepreneurship", approved by the Order of the Ministry of Education and Science of Ukraine No. 1221 from

07.10.2016, was proposed and conducted a training course for directors and semi-directors of preschool, secondary, vocational and higher education on the topic: "Implementation of economic approaches in the management of schools". During 2017–2019, 1225 training participants from all regions of Ukraine were covered. We chose the regions based on the openness of the regions themselves, readiness for change and training of their principals.

During the training, participants were interviewed on the following similar issues:

- Is the school an economic entity?
- Who is the client (s) of the school?
- What are the products (services) of a school (main and secondary)?
- What is the "raw material" of a school? What other resources are needed?

The results of the survey show a number of trends in education:

- for more than 50%, directors agreed that schools are part of economic systems;
- for 87% of participants the pupil / student is the raw material of the schools;
- the products of the school are graduates, competencies, certificates / diplomas;
- clients of the school are parents, the state, universities, sometimes businesses, public organizations;
- for some directors there is a rejection of the introduction of the principles of classical management in the management of schools and the need to understand economic issues.

These answers reflect the gap in the perception of the customer, product, input resources between schools and representatives of private business, in particular training and education centers, which clearly understand these positions. There are objective and subjective reasons for this situation.

Objective reasons:

- the legacy of the industrial economy – all had to be adjusted to the production system. Those who did not fit were either ruled out or "fell out" of the system of economic relations;
- absolutization of the state in the socialist system;
- low human value in the USSR.

Subjective reasons:

- unwillingness to change quickly and understand all the laws of a market economy;
- lack of tools for adaptation from systemic, public administration to autonomy and self-government;
- legislative "leapfrog" with changes and the possibility of rolling back reforms;
- non-acceptance of each other's educational and business community, different "languages", principles and approaches to solving issues.

These reasons are significant obstacles to the training of heads of schools in economic and managerial approaches. And in order to train managers and effectively retrain it is necessary to take into account the peculiarities of the implementation of the economic style of management of the organization.

The first economic management should be a system that covers all levels of operation: customers (pupils / students), teachers / lecturers, deputy principals and principals (figure 1).

At each level it is necessary to implement the approaches and methods. For leaders, it is recommended, first of all, to look at the entrusted school not from the point of view of a teacher, organizer, pedagogical manager, but from the point of view of an economic non-profit organization. Such an organization has many business processes, and which should function as efficiently as possible and use the allocated public funds from the state and / or local budgets.

This will help to develop economic thinking, which is based on a simple but vital position: any result should always be greater than the spent material, financial, informational, time resources. If such equality is not ensured, then such a solution should be revoked or implemented so as to reduce the cost of limited resources.

At the level of deputies, the range of responsibilities is radically expanding. Today it is not enough to be responsible and manage only educational activities. It is necessary to move to a full range of management in various areas:

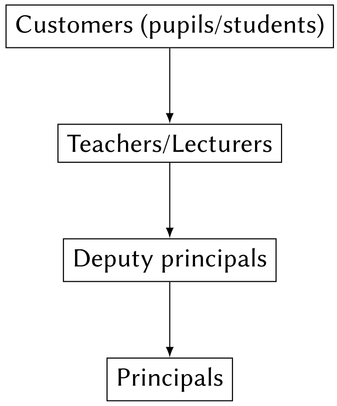

Figure 1: Development of entrepreneurial education.

- marketing of the school (information, image policy, admission campaign);
- financial (ensuring such a state that funds are always enough for all costs in full and at the right time);
- HR-management (to form an initiative and self-supporting team, which prevents moments of emotional burnout and recession).

Only in this case can we talk about the introduction of real autonomy and full management of the entire educational system.

However, building an effective internal governance mechanism does not yet guarantee the successful operation of the school as a whole. After all, any school significantly depends on the external environment and the influence of all stakeholder groups. The main such groups are other schools of different levels (both relevant and related), clients (students, parents), business as sponsors and as future employers for educational services, with the founders and authorities in the field of education.

Heads of schools take care of external communication. Because strong interaction and balance of educational programs must be built between different levels of education, so as to ensure a progressive and continuous learning process. After all, youth who enters the formal education system at 2 years and leaves it at 19-25 years, must clearly understand where and how to move in adult life, must be able to earn their skills, knowledge, be professional and acquire basic competencies (competencies in understanding of business).

This approach means that there can be no "gaps" in approaches, forms of learning at the intersection of educational levels. For example: the last year of kindergarten corresponds to the 1st grade of school, 9th grade – with the 1st year of college. Graduation from the 11th grade of the school opens opportunities for study in the first year of universities and high colleges.

Today, as in previous years, there is a big discrepancy between the last classes of school and the first months of study in university. Lecturers spend significant resources on adapting first-course students instead of effectively teaching them specialized disciplines and developing professional skills.

A similar situation arises between the 9th grade and the 1st year of VET. With the difference that the vocational education system often works to restore the student's motivation and try to direct him to adult life — because he did not fit into the "classical schemes" of schooling.

In interaction with the market of educational services, two key issues should be in focus. First, understanding what exactly the applicant for educational services, his parents, wants. Secondly, a clear answer to what exactly the community should allocate funds from the public budget intended to finance the school.

Regarding the first, the content of educational programs cannot be the same from year to year. On the contrary, it should be flexible, relevant to today's demands of young people. And the teachers themselves must also be modern, in demand in their subjects.

Regarding the second position, the value of educational services for the client, community (urban, rural, district, regional or national), an explanation of why budget funds are spent and what areas of training they should be allocated to benefit from it should be constantly confirmed by communities.

It is worth working with business as equal partners. Elevation in the status of the head of a school opens opportunities for greater maneuverability in interaction with business, as both parties are free to make their decisions in search of mutually beneficial proposals. For business, first of all, schools are interesting from the point of view of the employer and the ability to quickly find employees. This is an interaction in the dimension of the labor market. And, if the school can fully satisfy the requests for training, the support from the business is provided.

If not, the dialogue will not take place. It will be easier and even cheaper for a business to train a specialist than to retrain someone. The possibility of such an alternative should be constantly considered by the head of the school.

Another source of interaction with business is the provision of mediation services in the search for employees (the provision of employment services in the context of the labor market). Education organizations have practically ready and motivated employees. And there is an opportunity to test and find the right employee.

As for the state, it is essential to ensure "transparent" rules of the game (regulatory system), which will determine the working mechanisms for all participants in the educational process and stakeholders. Therefore, there is a need for internal and external security. This is especially important for Ukraine.

This understanding of the prerequisites for building the internal and external economic environment of the school contributes to the successful learning and further restructuring of the school on the basis of organizational, financial, personnel, academic autonomy.

4. Modern instruments of forming economic and managerial competencies

Economic and managerial (managerial) training of heads of schools pursues the main goal – to teach / improve the ability to generate ideas and implement them independently in the practice of autonomous and self-sufficient management of schools. And such training should take place not only by standard tools (lectures, seminars, trainings), but also by innovative methods with the involvement of game and simulation technologies. Because rapid, effective retraining of economic principles of managers, formed in a rigid hierarchy of public administration, is possible only by radical methods that directly affect thinking, behavior and form applied skills.

Among such technologies of innovative, fast and radical practical training of managers are:

- games [5];
- simulators [6];
- gamification [7];
- virtual reality [8].

Each technology is suitable for use in certain conditions in the presence / absence of technical support. Comparative characteristics of each of the technologies are:

- Games – need scenario, need rules, participants and trainers, less interest after 3-5 rounds of playing, we remember that it is only game. Minimum technical support.
- Simulations – learning by doing, need computer classes, not necessarily of trainers/moderators, reproduction of conditions of the real environment / object / process [9]. Normal technical support.
- Gamification – using of game practices and mechanisms in a non-game context in real life, technical, organizational and high-level need of resources, involvement of natural human instincts: competition, achievements, status, self-expression, altruism, problem solving, formation of skills in the process of training and real life or in a specially created environment [10]. Need medium technical support.

- Virtual reality – full immersion in a specially created environment, need special IT support and equipment, the participant virtually "lives" in such an environment, difficult exit from the environment [11]. Must have very high technical support.

When comparing different methods, the most appropriate to use are games and simulators, which are relatively easy to obtain, organize and conduct with minimal or sufficient (available to most users) technical conditions. As for gamification and virtual reality, today these tools are either not yet perfect, or are valuable in organization and use. And the use of such technologies requires considerable time and inclusion, which, as a matter of fact, does not have the heads of schools.

The use of game technologies, in particular, business games, in professional development of managers is sufficiently described in the pedagogical literature. But the issue of using simulators, in particular business simulators, is not covered enough, and is often unusual and new for the pedagogical management community [12].

Simulation technologies are interactive systems that reproduce the conditions of a particular environment, object, process using mathematical models [13, 14, 15, 16, 17, 18]. Examples of simulators are flight simulators, automobiles, locomotives, meteorological, physical, etc. Economics and business often use business simulators, which are interactive models of the real business environment in the form of a computer program that reproduces a structural unit of the company, an entire firm, industry or the economy of the whole country.

The history of creation and use of simulators is more than 50 years and has its roots in the military sphere. The leaders are Great Britain, the United States, Japan, Germany, and Scandinavian countries. In some countries, simulators are used at all levels of education – from preschool to adult education. Because this technology allows you to acquire practical skills and abilities.

A business simulation is a computer program, a large-scale interactive simulation system that is specifically designed to provide participants with economic and managerial competencies and skills. The main simulators are to create opportunities for the acquisition of practical skills in managing the economic processes of the entire technological chain of production, marketing and competition in the market environment, as well as the management of the enterprise as a whole. Today in the world there are hundreds of professional simulators with varying degrees of immersion and elaboration of processes. Ukraine also has its own products that are actively used in educational activities (figure 2).

Figure 2: Well-known business simulations in the world and Ukraine.

The effectiveness of gaining practical skills while participating in interactive business simulators is ensured by the application of the method of learning by doing (learning by doing), which gives the participant the opportunity to:

- not only observe the processes of functions of the enterprise, but also to make specific economic and managerial decisions that have real and adequate consequences for further activities;

- to acquire and improve theoretical knowledge of economics and management, to understand the causal links in the management of economic processes;
- simulators try to realistically reproduce the processes of functioning of the production enterprise, starting with the organization of production and ending with the sale of manufactured goods in conditions where there are different types of market – from duopoly to monopolistic competition.

After registration in the system, the participant receives an enterprise in an environment close to reality and has the opportunity to make economic and managerial decisions necessary for the start of its work and further development. The participant is given the opportunity to use existing financial instruments in Ukraine, to determine the range of products planned for production, to master it in production, to expand and modernize the production technological base, to hire and organize the work of personnel. Using appropriate marketing tools, the participant has the opportunity to start promoting and selling products.

In addition, it should be emphasized that the company is in a market environment, and when making decisions it is necessary to take into account the presence of other market participants. Thus, competition in the virtual market space forces the participant not only to look for effective tools and ways to promote the product, but also to make changes in the production process in order to change the consumer qualities of products and optimize its cost [19].

For teachers and management of schools, participation in business simulators is quite difficult, as it is necessary to master economic terminology, methods and approaches to decision-making in a market environment, analysis of decisions and results.

During 2015-2020, 120 trainings were held and as part of the annual business tournament "Company Strategy" a league of mentors was opened using the ViAL+ business simulator. About 600 leaders, deputies, teachers became participants. During this ViAL+ business simulation, the participant goes through several stages:

1) there is an adaptation to the simulation environment (5-6 periods);
2) a comprehensive vision of the company is formed as a system, which, at the same time, consists of interconnected functional units (10–12 periods);
3) the understanding of causal relations of management of economic processes of the enterprise in the competitive market environment (18–20 periods) is formed;
4) after that – conscious implementation and adjustment of the previously formed action plan, professional analysis of the results (after the 20th period);
5) consolidation of acquired competencies and practical skills occurs after 25 periods.

The usefulness and need for such trainings was noted, but there is also a significant entry threshold. In this regard, it is worth noting the necessary prerequisites for the use of business simulators in the retraining of managers and training of future managers:

- clear arrangement of tasks and setting to go beyond traditional learning and existing patterns;
- preparation of participants for economic terminology, logic of management decisions in market conditions;
- updating of digital skills of training participants;
- assistance with the first decisions, a full explanation of the consequences of decisions and what to look for;
- constantly explain the relationship between business processes and processes in schools in the light of the implemented reform of the education sector.

During 2018–2020, 230 managers, deputy heads of secondary, vocational, higher education institutions or their structural subdivisions were trained using simulators. For 67% there was a significant and quite significant increase in ownership of economic and managerial competencies.

5. Conclusions

Complex and systematic use of various innovative pedagogical technologies in the process of professional development of vocational school leaders makes it possible to rationally use teaching time, motivate students to self-development and self-improvement, while increasing the level of psychological, methodological, didactic and managerial competence.

The technology of professional development of heads of vocational schools has its own specifics, structure, stages. It is an effective tool for achieving professional self-improvement, acme peaks, competencies on a spiritual-axiological basis, initiation of rethinking, self-overcoming, self-determination, self-realization of a specialist, creative transformation of all professional activities based on conscious self-development.

The study does not cover all aspects of the problem. The subject of further scientific research may be the study of foreign experience of professional self-improvement of heads of vocational schools; development of effective pedagogical technologies aimed at improving personal and professional qualities, in particular through a set of psychological and pedagogical trainings and self-trainings.

To further improve the training, it is necessary to create a specialized simulation of schools in terms of economic and organizational autonomy. This project envisages the creation of an existing simulation, which will model the activities of the school and the competitive economic environment, the creation of a simulation by all participants. Such a simulation will be designed to prepare principals, deputy principals, teachers-methodologists to work in the new conditions of the school, in which funds will be allocated not to a particular school, but to students in the form of certificates. This will force schools to fight for the attraction of more able students, and, accordingly, will open space for competition between schools and create conditions for improving the quality of educational services for students.

Thus, modern changes in legislation and the reform of schools are forcing the search for innovative ways of training, education and retraining of managers in educational activities. Such tools include game and simulation technologies. Today, you should use leading business simulators. However, in the future we will hope for the implementation of a specialized simulation of schools.

References

[1] Verkhovna Rada of Ukraine, Zakon Ukrayiny “Pro osvitu” [Law of Ukraine “On education”], 2017. URL: https://zakon3.rada.gov.ua/laws/show/2145-19.

[2] Verkhovna Rada of Ukraine, Zakon Ukrayiny “Pro fakhovu peredvyshchu osvitu” [Law of Ukraine “On professional higher education”], 2019. URL: https://zakon.rada.gov.ua/laws/show/2745-19/print.

[3] Verkhovna Rada of Ukraine, Pro profesiynu (profesiyno-tekhnichnu) osvitu [On professional (vocational) education], 1998. URL: https://zakon.rada.gov.ua/laws/show/103/98-%D0%B2%D1%80/print.

[4] Verkhovna Rada of Ukraine, Zakon Ukrayiny “Pro povnu zahalnu serednyu osvitu” [Law of Ukraine “On complete general secondary education”], 2020. URL: https://zakon.rada.gov.ua/laws/show/463-20.

[5] O. M. Haranin, N. V. Moiseienko, Adaptive artificial intelligence in RPG-game on the Unity game engine, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 1st Student Workshop on Computer Science & Software Engineering, Kryvyi Rih, Ukraine, November 30, 2018, volume 2292 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018, pp. 143–150. URL: http://ceur-ws.org/Vol-2292/paper16.pdf.

[6] D. S. Antoniuk, T. A. Vakaliuk, V. V. Didkivskyi, O. Vizghalov, O. V. Oliinyk, V. M. Yanchuk, Using a business simulator with elements of machine learning to develop personal finance management skills, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 9th Illia O. Teplytskyi Workshop on Computer Simulation in Education (CoSinE 2021) co-located with 17th International Conference on ICT in Education, Research, and Industrial Applications:

Integration, Harmonization, and Knowledge Transfer (ICTERI 2021), Kherson, Ukraine, October 1, 2021, volume 3083 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 59–70. URL: https://ceur-ws.org/Vol-3083/paper131.pdf.

[7] E. G. Fedorenko, N. V. Kaidan, V. Y. Velychko, V. N. Soloviev, Gamification when studying logical operators on the Minecraft EDU platform, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 107–118. URL: https://ceur-ws.org/Vol-2898/paper05.pdf.

[8] S. O. Semerikov, M. M. Mintii, I. S. Mintii, Review of the course "Development of Virtual and Augmented Reality Software" for STEM teachers: implementation results and improvement potentials, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 159–177. URL: https://ceur-ws.org/Vol-2898/paper09.pdf.

[9] O. Pavlenko, D. Velykodnyi, O. Lavrentieva, S. Filatov, The Procedures of Logistic Transport Systems Simulation into the Petri Nets Environment, in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 854–868. URL: https://ceur-ws.org/Vol-2732/20200854.pdf.

[10] O. O. Katsko, N. V. Moiseienko, Development computer games on the Unity game engine for research of elements of the cognitive thinking in the playing process, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 1st Student Workshop on Computer Science & Software Engineering, Kryvyi Rih, Ukraine, November 30, 2018, volume 2292 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018, pp. 151–155. URL: http://ceur-ws.org/Vol-2292/paper17.pdf.

[11] P. Nechypurenko, O. Evangelist, T. Selivanova, Y. O. Modlo, Virtual Chemical Laboratories as a Tools of Supporting the Learning Research Activity of Students in Chemistry While Studying the Topic "Solutions", in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 984–995. URL: https://ceur-ws.org/Vol-2732/20200984.pdf.

[12] O. V. Komarova, A. A. Azaryan, Computer Simulation of Biological Processes at the High School, in: A. E. Kiv, V. N. Soloviev (Eds.), Proceedings of the 1st International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, October 2, 2018, volume 2257 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018, pp. 24–32. URL: https://ceur-ws.org/Vol-2257/paper03.pdf.

[13] D. S. Antoniuk, T. A. Vakaliuk, V. V. Didkivskyi, O. Y. Vizghalov, Development of a simulator to determine personal financial strategies using machine learning, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 4th Workshop for Young Scientists in Computer Science & Software Engineering (CS&SE@SW 2021), Virtual Event, Kryvyi Rih, Ukraine, December 18, 2021, volume 3077 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 12–26. URL: http://ceur-ws.org/Vol-3077/paper02.pdf.

[14] A. O. Devos, I. O. Torbenko, T. V. Doroshenko, V. V. Revenko, A. V. Shuhaiev, The application of the simulation method in the in foreign language teaching in higher education institutions, the cognitive linguistic approach, Journal of Educational and Social Research 11 (2021) 0072. doi:10.36941/jesr-2021-0072.

[15] A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk, 9th Illia O. Teplytskyi Workshop on Computer Simulation in Education, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 9th Illia O. Teplytskyi Workshop on Computer Simulation in Education (CoSinE 2021) co-located with 17th International Conference on ICT in Education, Research, and

Industrial Applications: Integration, Harmonization, and Knowledge Transfer (ICTERI 2021), Kherson, Ukraine, October 1, 2021, volume 3083 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. i–xx. URL: https://ceur-ws.org/Vol-3083/paper000.pdf.

[16] O. Tsvetkova, O. Piatykop, A. Dzherenova, O. Pronina, T. A. Vakaliuk, I. Fedosova, Development and implementation of virtual physics laboratory simulations for enhanced learning experience in higher education, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 98–110. URL: https://ceur-ws.org/Vol-3679/paper10.pdf.

[17] R. Balabay, E. Chernonog, Alteration on the surface of the pore walls of the porous silicon under high temperature ageing: Computer simulation, Radiation Measurements 42 (2007) 739–741. doi:10.1016/j.radmeas.2007.02.069.

[18] P. A. Chaika, V. A. Minko, An installation for simulating pneumoconioses involving physical stressing of test animals (Russian), Meditsina Truda I Promyshlennaya Ekologiya 18 (1974) 54–55.

[19] V. Pazdrii, P. Banschykov, V. Kosyk, I. Tropina, O. Hryshchenko, Simulation System in Educational and Career Guidance State Policy of Ukraine, in: V. Ermolayev, F. Mallet, V. Yakovyna, V. S. Kharchenko, V. Kobets, A. Kornilowicz, H. Kravtsov, M. S. Nikitchenko, S. Semerikov, A. Spivakovsky (Eds.), Proceedings of the 15th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kherson, Ukraine, June 12-15, 2019, volume 2393 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 935–943. URL: https://ceur-ws.org/Vol-2393/paper_428.pdf.

The educational technology landscape in Ukraine

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Abstract

The adoption of digital technologies in education has accelerated rapidly in recent times, driven by technological progress and catalyzed by the global COVID-19 pandemic. This article analyzes the present landscape and future prospects for Educational Technology (EdTech) in Ukraine. Efficiency analyses using Data Envelopment Analysis methodology reveal substantial opportunities for Ukraine to enhance educational outcomes via increased investment and technology integration. Ukraine's EdTech startup ecosystem has expanded to over 80 companies delivering solutions spanning tutoring, language instruction, MOOCs, K-12 education, STEM fields, robotics, learning management platforms, and more. However, a strategic assessment indicates the ecosystem currently faces more challenges and risks relative to advantages and possibilities. Major obstacles include high financial costs, regulatory impediments, underdeveloped technical infrastructure, resistance to change among educators, and limited data on the impact of EdTech. For Ukraine to fully realize the potential of EdTech, concerted efforts are needed to boost public and private investment, fast-track digitalization initiatives, foster an enabling environment for EdTech enterprises, and develop educators' capacity to effectively incorporate technology. With focused strategic interventions, EdTech can serve as a key engine for expanding access, elevating quality and driving efficiency gains in Ukraine's education system.

Keywords

educational technology, Ukraine, digitalization, efficiency, COVID-19, startups, technology integration, government policy, teacher professional development

1. Introduction

Innovation in technology is swiftly reshaping all facets of society, and the education sector is no exception. However, the speed of digitalization in education has traditionally trailed other industries due to elevated costs, sophisticated functionality of solutions, and inertia in evolving pedagogical methods [1, 2]. The COVID-19 pandemic marked a turning point, compelling educational institutions globally to rapidly transition to distance learning modalities and spurring investment and adoption of educational technologies [3, 4].

In Ukraine, the EdTech sector was already expanding before the pandemic but has since experienced a boom. By 2020, the Ukrainian EdTech ecosystem encompassed over 80 startups offering products and services targeting learners across age groups. This paper aims to evaluate the existing landscape and future outlook for EdTech in Ukraine, exploring key trends, prominent companies, opportunities and challenges.

2. Education efficiency analysis

The evaluation of the effectiveness of education in Europe and Central Asia by the Data Envelopment Analysis (DEA) method, where the input – Expenditure on education, output – GDP per capita (figure 1).

The results of the analysis showed that effective education (efficiency coefficient equal 1) in Greece, Italy, Ireland, and Switzerland. Norway, France, Austria, Germany, Finland, the Netherlands, and Iceland

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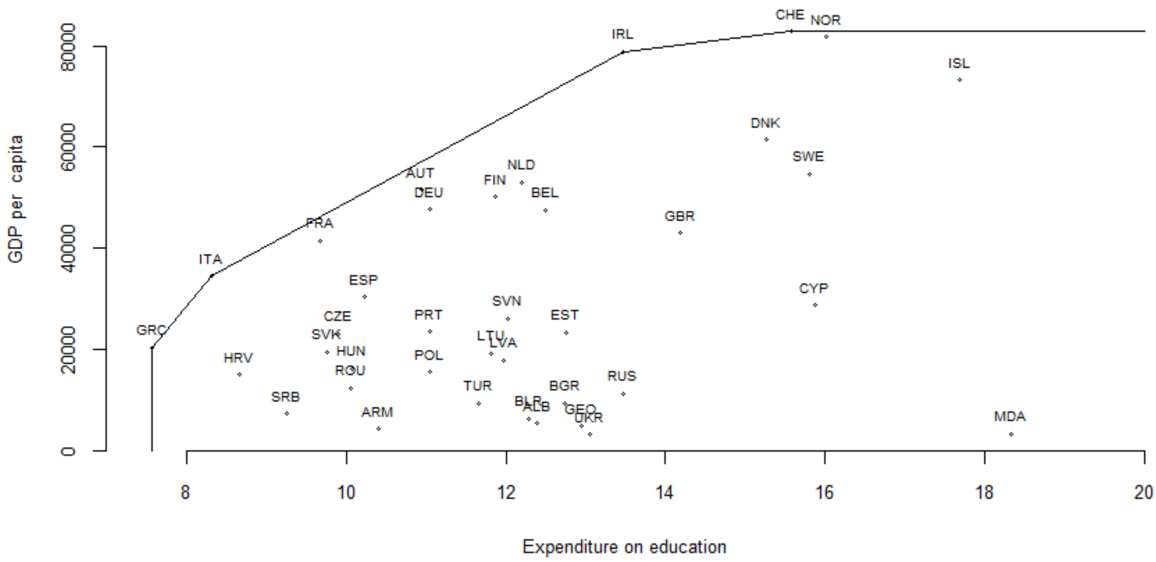

Figure 1: Data Envelopment Analysis of expenditure on education.

are close to the efficiency curve. That is, European countries, in general, have experience in the effective expenditure on education. As for Ukraine, the expenditure on education is extremely inefficient, a similar situation in Georgia, the Russian Federation, and Moldova (ie in the countries of the former USSR).

Employee education is the key to a company's success. That is why companies try to get highly educated employees and maintain their qualifications at a high level. To assess the effectiveness of education in Europe and Central Asia, built a model of DEA, where inputs – GDP per capita, Internet users (per 100 people), Expenditure on education as (% School-age population, output – Labor force with advanced education (% of the total labor force). The simulation results are shown in the table 1.

Table 1
Data Envelopment Analysis of education effectiveness.

Efficiencies range	Number of countries	%	Countries
$0.7 \leq E < 0.8$	5	11.4	Belgium, Denmark, Germany, Netherlands, United Kingdom
$0.8 \leq E < 0.9$	10	22.7	Austria, Czech Republic, Finland, France, Ireland, Norway, Russian Federation, Spain, Sweden, Switzerland
$0.9 \leq E < 1$	8	18.2	Albania, Belarus, Bulgaria, Hungary, Italy, Poland, Slovak Republic, Slovenia
$E = 1$	21	47.7	Croatia, Cyprus, Estonia, Georgia, Greece, Iceland, Latvia, Lithuania, Luxembourg, Moldova, Portugal, Romania, Serbia, Turkey, Ukraine

DEA model analyzing efficiencies by VRS technology and input orientated efficiency. A number of countries with efficiency equal 1 are 21 out of 44, mean efficiency: 0.922.

The results show that efficiency is lower in those countries that incur significant expenditures on education. Conversely, countries with low spending on education have shown high efficiency. For example, Ukraine has an efficiency of 1, Labor force with advanced education – 72.15, GDP per capita – 3095.17, Internet users (per 100 people) – 89.74, Expenditure on education – 13.05, School-age population – 3.9 million. Germany, the efficiency of which is 0.72, has Labor force with advanced education – 73.56, GDP per capita – 47603, Internet users (per 100 people) – 71.13, Expenditure on education – 11.04, School-age population – 2.5 mln.

Analysis of education efficiency in different countries has shown that there is great potential for productivity increases. Therefore, the implementation of innovations in education is promising.

3. Investing in educational startups

Holon IQ is an international analytical agency founded in 2018 [5]. Initially, the company invested in educational startups but switched to market analysis to help more projects. According to the Holon IQ estimates (figure 2), global education venture capital funding in 2022 decreased to $10.58 billion, which is more than twice lower that in 2021. Logically, this is a direct consequence of the COVID-19 pandemic and the quarantine that forced everyone around the world to go online. In the context of expected changes in the structure of the labor market, EdTech tools will continue to be in demand for the acquisition of new skills and retraining of employees. Note that China invests the most in educational programs, for example, US funding is 2 times less than China, and European funding is 10 times less (in total for the last 10 years).

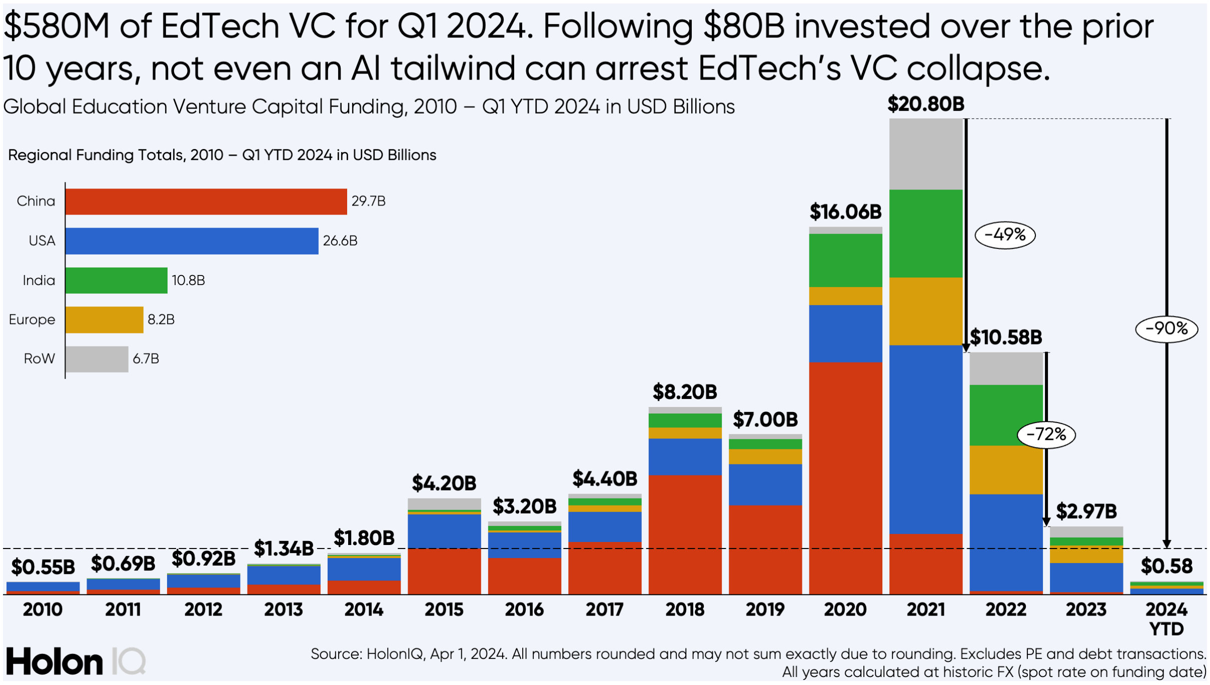

Figure 2: Global education venture capital funding, 2010–2023 in USD Billions [6].

Globally, most major markets have followed a similar trajectory with steady climbs into the pandemic, followed by 2-3 year surges in investment before falling back to investment levels not seen for around 7 years in Europe, 10 years for the US and nearly 15 years in China.

HolonIQ listed the 200 best EdTech companies in Europe, where 11 projects from Ukraine are included. The rating is based in:

- companies market positions;
- demand and quality of products;
- financial stability;
- attractiveness for investment;

- development progress and dynamics;
- project team.

Ukrainian EdTech projects listed in the HolonIQ rating:

- Basenji Apps – applications for English learning;
- EnglishDom – online school of English learning;
- Enguide – service for choosing English courses in Kyiv;
- Speechyard – service for learning English by movies;
- Besmart – preparation courses for final exams at school;
- SkillUp – training courses for IT specialists;
- Skyworker – service for finding IT vacancies;
- Jooble – job search service;
- Parta – educational portal;
- Studway – media about education;
- Vseosvita – service for continuing education.

As we can see, the most popular are services for learning English. But there are nearly 80 digital education projects in the Ukrainian EdTech landscape. EdTech Landscape map of Ukraine for 2020 (figure 3) was proposed by Vadym Synzheretskyi (CEO and co-founder of BUKI online platform for tutors).

4. Ukraine EdTech ecosystems analysis

Synzheretskyi [8] proposed to cluster EdTech ecosystem of Ukraine in such a way: Tutoring; Language learning; MOOC; School Education (K-12); STEM & coding, Robotics; Information platforms; For teachers; LMS (learning management system); IT Education; Upskilling; Tools; Talent. Let's look at the examples from each group.

Preply [9] is an online educational platform that connects tutors and teachers (from 185 countries) with students, locally or virtually via Skype. In March 2020, the Ukrainian EdTech marketplace for the study of foreign languages Preply got $ 10 million, almost twice the amount of all previous investments ($ 5.6 million). The service uses machine learning algorithms to match tutors. The company plans to launch new tools for teachers that will help assess homework, monitor progress, and help students more effectively. The company also plans to develop a mobile application for Android and iOS.

EnglishDom [10] is an online English school and at the same time an IT company that inspires to learn English through technology. The company is one of the leaders in the field of EdTech in Eastern Europe. The EnglishDom platform includes 5 innovative services for learning English, including mobile applications and an interactive digital textbook. The service unites more than 500 English teachers and 50,000 users.

Prometheus [11] is a mass online courses platform called "Ukrainian Coursera". The main goal of the project is to provide free online access to university-level courses to anyone, as well as to provide opportunities to publish and distribute such courses to leading professors, universities, and companies. Upon completion of the course, the student receives a certificate signed by the best teachers of Ukrainian universities. Today the platform has more than 300 thousand active users. Prometheus has organized its free online in-service training courses for educators in accordance with the requirements of the Procedure for in-service training of pedagogical and research and teaching staff. Prometheus online course certificates for educators can be officially credited as advanced training.

EdPro [12] is one of the few Edtech solutions for school education. This interactive panel can replace several objects in the classroom at once – a blackboard, a projector, an interactive screen, and a computer. In such panels, teachers can show students presentations, videos, graphics, or images during lessons. Instead, students can solve learning tasks, count, or edit texts right away. Along with the board, they also developed an interactive software solution for education with illustrations and

Figure 3: EdTech Landscape of Ukraine [7].

animations. Apparently, the next interesting area of EdTech will be the use of augmented and virtual reality technologies. The development of this area will lead to the fact that students will increasingly move from passive to active learning and will be able to interact in real-time with educational material, which will stimulate their motivation and increase the level of interest. This opens up exciting prospects for teaching new generations.

Osvitoria [13] propose interesting and up-to-date news about modern education and stories on how to change the system of education in any conditions and become a better version of yourself every day. They create a user-friendly platform for teachers and parents to help them find answers to their children's education and upbringing and to involve parents in the learning process. They try to give teachers effective tools for communication, the opportunity to learn about the best practices of teaching abroad, the latest news on education reform.

In addition to quality analytics, there are many different selections, articles about the needs of students and teachers with options for proposals that can be done in a particular situation. Teachers can take great advice to improve their work, and parents - to improve the well-being or performance of their children.

The educational project **Na Urok** [14] aims to objectively cover the modern educational process and bring it to a qualitatively new level. This became possible due to the implementation of versatile and thorough work: writing informative articles related to school and extracurricular life; conducting thematic webinars; introduction of various educational competitions; attracting the best developments in school subjects from teachers from all over Ukraine. The project aims to help teachers feel their own significance because each teacher in the project will be able to publish their own professional achievements or use the work of colleagues. The project is set up to work closely with educators who want to share their experiences on the Internet. The Na Urok team makes a significant effort to ensure that teachers, parents, and students can find the maximum amount of useful theoretical and practical materials for the school on the portal.

The **eTutorium** [15] project aims to organize distance learning through the implementation of effective IT solutions. The project arose in 2008 from attempts to create their own webinar platform to conduct online events. After analyzing the needs of the eLearning market, in 2010 the team moved on to developing solutions for online tutors. Today, the platform hosts between 3,200 and 5,000 webinars per month. In 2015, we launched the eTutorium project, combining an updated platform for eTutorium Webinars and eTutor Academy – the Academy of Tutors, where we share our experience and knowledge in the field of online learning. In 2019, they created eTutorium LMS – a system of distance learning, with which you can not only collect courses but also fully organize the learning process online.

Mate academy [16] is an online platform for learning programming and finding your first job in IT.

Table 2
Comparative study of the EdTech projects.

EdTech project	Type	Advantages	Disadvantages
Preply	Tutoring	Reaching a large audience. The use of machine learning in management.	Communication local or Skype. Absents of mobile applications.
EnglishDom	Language learning	Use innovative services and mobile applications. Reaching a large audience.	Lack of offline support.
Prometheus	MOOC	Use mobile applications. Reaching a large audience.	The audience is limited to Ukrainian-speaking users.
EdPro	School Education	Use innovation technologies. Good motivation for students. Opportunities for different applications.	High cost of the product
Osvitoria. Media	LMS	A large amount of information about various aspects of the educational process	Lack of mobile application
Na Urok	Information platforms	A good motivational approach. Coverage of a large number of educational topics.	No mobile application. A small audience of parents and students.
eTutorium	For teachers	A successful solution for organizing online learning. Great prospects for further development.	Having strong competitors with free solutions.
Mate academy	IT Education	Opportunities to expand the audience. Large set of programming courses.	Risks of non-payment for training.
Grammarly	Tools	Ease of use. Wide audience of users. Constant demand for products.	English spelling only.

The training lasts 4-5 months and takes place online. Now in the portfolio of Mate academy courses includes Java, Front-end, Full Stack Web, UI / UX Design. The peculiarity of the platform is that students pay for their studies only in case of employment, giving a percentage of the new salary. During the existence of Mate academy, more than 200 students got jobs. In 2020 the company was planning to open a business in new markets; They looked at the country, where there is a great demand for engineers and the road, for no worse than the knowledge. The aim of the company in 2022 there were a number of thousands of engineers in Ukraine and the English regions – for example, Great Britain and India.

Grammarly [17] is one of the most famous Ukrainian startups. This is a service for checking written texts. It helps to correct grammatical and stylistic errors. A free version is available, as well as Premium, which expands access to additional features. The company's head office is now located in Silicon Valley, and the service was founded by three Ukrainians. In 2019, it became known that the total amount of investment in Grammarly is about $ 200 million (5 billion hryvnias). This funding has raised the company's total value to more than $ 1 billion. So from now on the Ukrainian startup can be officially called a "unicorn". Grammarly services are now used by millions of regular users around the world. We are talking only about English-speaking users, the developers do not plan to expand the number of languages for testing yet. As of 2020, 30 million people use Grammarly services every day.

5. SWOT analysis on EdTech system of Ukraine

The key task of education in modern conditions is to change, adapt to new conditions, and develop. The analog world is becoming increasingly fragile, and the digital world is becoming antifragile. COVID-19 not only posed threats to agriculture but also opened up new opportunities, in particular in digitalization and the introduction of innovative technologies. In our opinion, education in Ukraine needs the introduction of a significant number of EdTech, which will accelerate the development of education and increase its efficiency. SWOT analysis of the EdTech startup ecosystem is presented in table 3.

Table 3
SWOT analysis on EdTech system.

INTERNAL FACTORS	
Strengths	**Weakness**
The government starts to implement digital technology in education. There is a demand for digital education and innovative technologies in education from both business and private. Effective solutions that promise an increase in productivity	The high cost of innovative technologies. Problems with finding financing. The delayed effect of digital technologies implementation can decrease the effect of its realization. Unreadiness for change. The established habits of teachers and the lack of new skills and abilities. Bureaucratic hurdles for starting a business. Underdeveloped IT infrastructure Lack of information on the effectiveness of EdTech.
EXTERNAL FACTORS	
Opportunities	**Threats**
Education is a big area with a lot of students and pupils, which can demand many EdTech projects. The application of EdTech produces a lot of data that can be used for agriculture development. EdTech can significantly reduce the need for teachers and administrated staff.	If the EdTech is not reliable enough and accessible to attackers, the danger may arise for education. The probability of different EdTech results in different conditions. Access to data can increase inequalities, impede competition, and create economic barriers.

6. Conclusion and future work

Nowadays education needs to improve and increase efficiency. EdTech can become exactly the direction that will promote the active development of education, increase its accessibility and improve its quality. Analysis of the effectiveness of education has shown that the countries of Europe and Central Asia have significant potential for the development of education.

The EdTech startup ecosystem is characterized by more weaknesses and threats than strengths and opportunities. Ukrainian education has significant potential for increasing efficiency and development. To ensure the realization of this potential, it is necessary to do the following:

- increase government spending on education, in particular on the development of innovative technologies;
- ensure access of EdTech to financing;
- accelerate the process of digitalization of education, in particular, to promote the spread of affordable ICT and introduce e-government;
- increase the interest of non-governmental organizations in the introduction of innovative technologies in education;
- create favorable conditions for the development of EdTech ecosystems.

Further development of the EdTech startup ecosystem can be a key solution for the development not only in Ukraine but also around the world.

References

[1] O. V. Bondarenko, O. V. Hanchuk, O. V. Pakhomova, I. M. Varfolomyeyeva, Digitalization of geographic higher education: Problems and prospects, Journal of Physics: Conference Series 2611 (2023) 012015. doi:10.1088/1742-6596/2611/1/012015.

[2] A. V. Morozov, T. A. Vakaliuk, I. A. Tolstoy, Y. O. Kubrak, M. G. Medvediev, Digitalization of thesis preparation life cycle: a case of Zhytomyr Polytechnic State University, in: T. A. Vakaliuk, V. V. Osadchyi, O. P. Pinchuk (Eds.), Proceedings of the 2nd Workshop on Digital Transformation of Education (DigiTransfEd 2023) co-located with 18th International Conference on ICT in Education, Research and Industrial Applications (ICTERI 2023), Ivano-Frankivsk, Ukraine, September 18-22, 2023, volume 3553 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 142–154. URL: https://ceur-ws.org/Vol-3553/paper14.pdf.

[3] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, V. N. Soloviev, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, V. R. Ruban, Mask and Emotion: Computer Vision in the Age of COVID-19, in: Digital Humanities Workshop, DHW 2021, Association for Computing Machinery, New York, NY, USA, 2022, p. 103–124. doi:10.1145/3526242.3526263.

[4] S. G. Fashoto, Y. A. Faremi, E. Mbunge, O. Owolabi, Exploring structural equations modelling on the use of modified UTAUT model for evaluating online learning, Educational Technology Quarterly 2024 (2024) 319–336. doi:10.55056/etq.734.

[5] HolonIQ. Global Impact Intelligence, 2024. URL: https://www.holoniq.com/.

[6] EdTech VC collapse at $580M for Q1. Not even an AI tailwind could hold up this 10 year low, 2024. URL: https://www.holoniq.com/notes/edtech-vc-collapse-at-580m-for-q1-not-even-an-ai-tailwind-could-hold-up-the-10-year-low.

[7] T. Gritcyk, Predstavlena vtoraia versiia karty ukrainskikh obrazovatelnykh proektov — EdTech Landscape 2.0 (The second version of the map of Ukrainian educational projects is presented – EdTech Landscape 2.0), 2020. URL: https://ain.ua/2020/09/16/edtech-landscape-2-0/.

[8] V. Synzheretskyi, [TechUkraine news] EdTech Landscape of Ukraine 2020, 2020. URL: https://techukraine.org/2020/04/16/techukraine-news-vadym-synzheretskyi-ceo-of-%D1%80%D0%B5/.

[9] Learn languages with expert online tutors. Book your lesson today!, 2021. URL: https://preply.com/.

[10] Anhliiska po Skaipu - navchannia anhliiskii movi po Skype v EnglishDom, 2021. URL: https://www.englishdom.com/.
[11] Prometheus – Naikrashchi onlain-kursy Ukrainy ta svitu, 2021. URL: https://prometheus.org.ua/.
[12] Interaktyvna panel EdPro, 2021. URL: https://edpro.ua/.
[13] Osvitoria, 2021. URL: https://osvitoria.org/en.
[14] Osvitnii proekt "Na Urok" dlia vchyteliv, 2021. URL: https://naurok.com.ua/.
[15] Platforma eTutorium Webinar — maidanchyk dlia provedennia vebinariv ta treninhiv, 2021. URL: https://etutorium.com.ua/.
[16] Kursy Prohramuvannia i Dyzainu onlain z pratsevlashtuvanniam v Kyievi | Mate academy, 2021. URL: https://mate.academy/.
[17] Grammarly: Free Online Writing Assistant, 2021. URL: https://www.grammarly.com/.

Shifting sands: analyzing trends in educational technology research published in Educational Technology Quarterly (2021-2023)

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Abstract

Educational technology is dynamic, with new developments and innovations continuously shaping research directions and priorities. The Educational Technology Quarterly (ETQ) offers valuable insights into evolving trends within this domain through its broad publication of studies across various educational contexts and technologies. This paper provides a bibliometric analysis of research articles published in ETQ from 2021-2023 to identify key themes and changes in focus over this period.

Keywords

educational technology, bibliometric analysis, research trends, digital competence, blended learning, cloud computing, COVID-19 impact, Educational Technology Quarterly

1. Introduction

Educational technology encompasses a broad range of topics related to using technological tools and innovations to facilitate and enhance teaching and learning. As new technologies emerge and pedagogical paradigms evolve, this domain's focal points and priorities are constantly shifting. Tracking and analyzing these trends is crucial for understanding the state of the field and where research efforts should be directed going forward.

The scholarly journal *Educational Technology Quarterly* (ETQ) offers a valuable window into contemporary developments and discussions within educational technology research [1]. Published by the *Academy of Cognitive and Natural Science* (ACNS) [2], ETQ has established itself as a prominent platform for disseminating high-quality studies. Its broad scope spans diverse technological contexts and educational levels, from pre-school to higher education and life-long learning. As such, the body of literature published in ETQ represents a rich dataset for investigating evolving priorities and themes over time within this dynamic field.

This paper undertakes a bibliometric analysis of ETQ articles published over a recent three-year period (2021-2023). Examining patterns and changes in the topics covered during this window aims to

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elucidate the current landscape and trajectories of educational technology research. ETQ was selected as the focal journal for several key reasons:

- Its longevity provides a sufficiently large dataset for longitudinal analysis over multiple years.
- As an established, peer-reviewed journal, ETQ content represents cutting-edge findings in the field.
- In the meantime, ETQ content is not indexed by the leading scientometric databases like Scopus and Web of Science.

Therefore, ETQ constitutes an ideal case study for systematically mapping educational technology research trends and developments through bibliometric techniques. The findings will shed light on the prevalent topics of inquiry today and how priorities are shifting over time.

2. Methodology

The dataset for this bibliometric study comprised 72 research articles published in the Educational Technology Quarterly (ETQ) from 2021-2023 [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74]. Article metadata, including titles, abstracts, keywords, and publication dates, were retrieved using the journal's website in BibTex format.

Full-text abstracts for each article were extracted from the BibTeX files. Abstract texts were preprocessed by converting all text to lowercase, removing stop words and punctuation, lemmatization, and stemming. This produced a corpus of cleaned abstract text ready for bibliometric analysis.

The VOSViewer software tool was used to conduct the abstract corpus's bibliometric analysis. Specifically, VOSViewer was used to extract author keywords and generate and visualize maps of co-occurring keywords in the text. Abstracts were input to VOSViewer to identify frequent terms and filter out terms that occurred fewer than ten times. This resulted in 2134 extracted terms, of which 29 met the minimum occurrence threshold 10.

Various bibliometric techniques were applied to analyze this set of frequent keywords:

- Keyword analysis to determine the frequency of topics
- Temporal analysis of publication dates and topics
- Network analysis of co-occurrences between keywords
- Geographic analysis of author locations

These techniques provided quantitative indicators and visual mappings to elucidate the salient themes and trends within the dataset.

3. Analysis and discussion

3.1. Keyword analysis

The co-occurrence network map generated in VOSViewer provided valuable visualizations of the relationships and clusters among frequent keywords in the ETQ dataset. As shown in figure 1, five distinct clusters emerged.

Cluster 1 centers on keywords such as “digital competence”, “information”, and “system”, indicating a focus on developing digital skills and utilizing technology systems.

Cluster 2 contains keywords like “blended learning”, “concept”, and “practice”, reflecting research on pedagogical models and educational concepts.

Cluster 3 includes keywords such as “cloud”, “environment”, and “model”, relating to technological infrastructure and frameworks.

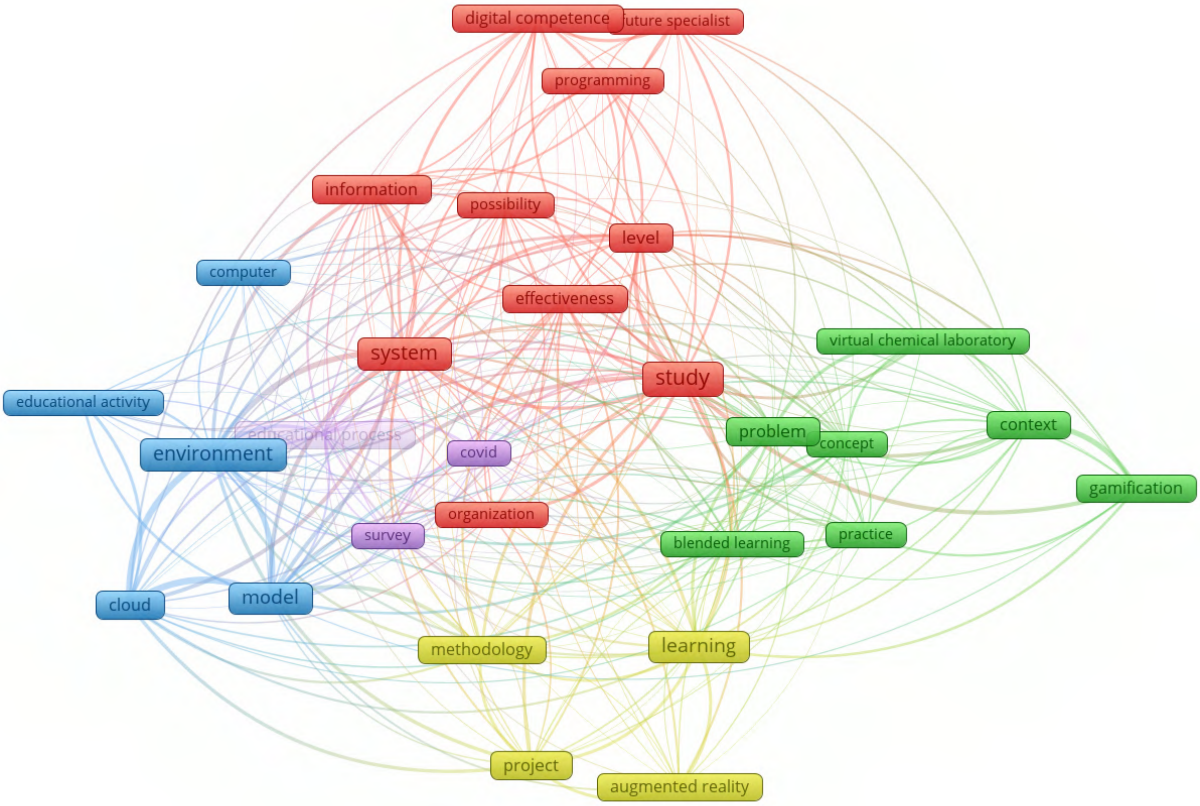

Figure 1: Co-occurrence network of keywords.

Cluster 4 contains keywords like "methodology", "project", and "study", potentially pointing to research methods and processes.

Finally, cluster 5 contains keywords such as "covid", "educational process", and "survey", signalling research undertaken in response to the COVID-19 pandemic.

Notably, the keywords "learning", "level", "problem", and "effectiveness" occupy central positions spanning multiple clusters. This suggests they represent interdisciplinary topics connecting these research domains.

The scattered peripheral keywords "future specialist", "programming", and "virtual chemical laboratory" indicate more niche focus areas studied.

3.2. Temporal analysis

Mapping the keywords by their publication dates reveals several interesting temporal patterns and changes in research focus over time (figure 2).

Terms related to the COVID-19 pandemic, including "covid", "survey", and "educational process", emerged abruptly in 2021 and remained frequent throughout the dataset, reflecting a surge in pandemic-driven research.

"Cloud" first gained traction in 2021, pointing to growing attention on cloud-based technologies and remote learning during the pandemic's onset. This term has continued trending upward, signalling sustained focus in this area.

In contrast, keywords like "gamification" and "virtual chemical laboratory" only gained prominence in 2022 and 2023, respectively, indicating these were newer rising topics of inquiry.

Terms such as "model", "practice", and "organization" displayed peaks in 2021 before declining over 2022-2023. This suggests certain research priorities were more time-bound to the pandemic's early stages.

By 2023, keywords like "methodology", "problem", and "programming" overtook some earlier topics

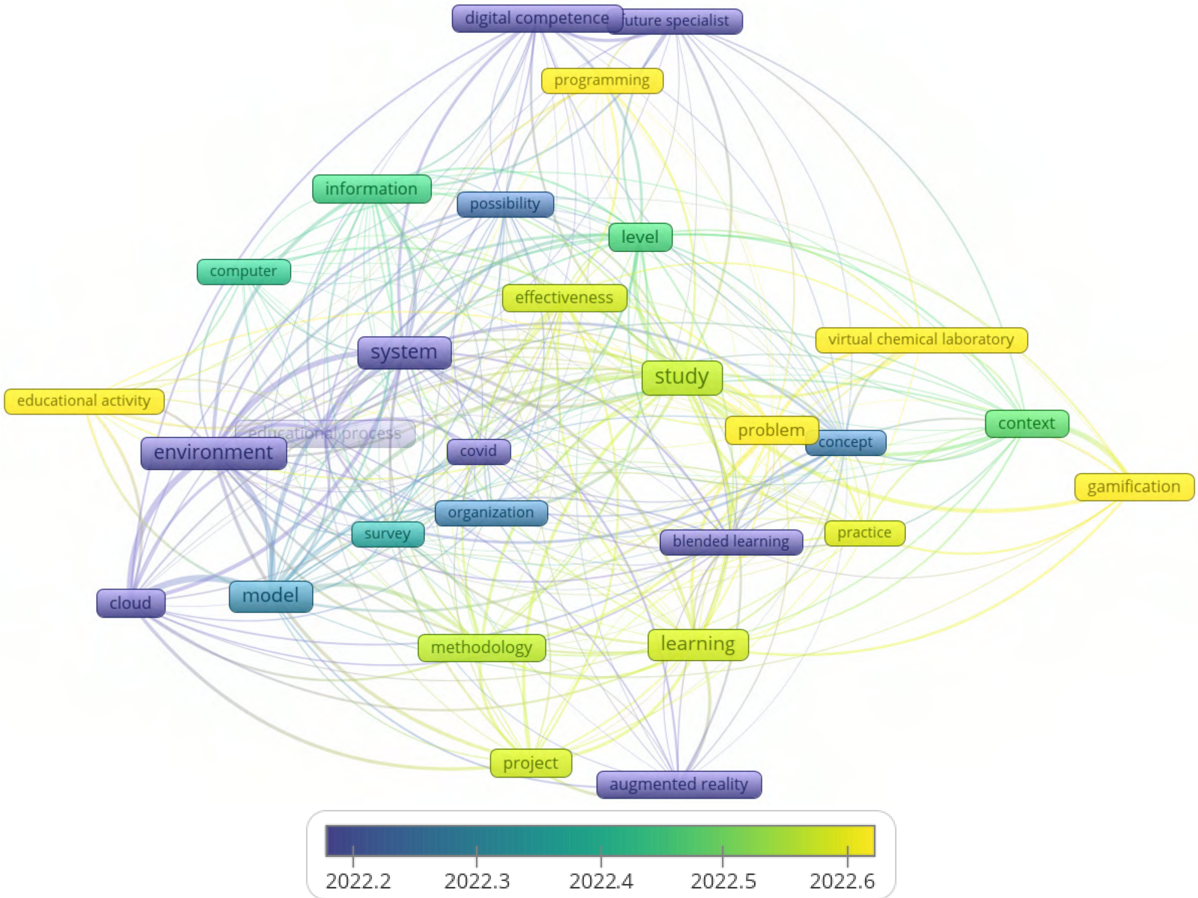

Figure 2: Overlay visualization.

in frequency, indicating a return to more foundational educational technology research as the acute pandemic period receded.

Notably, "digital competence" first rose substantially in 2022, and its upward trajectory continued through 2023, pointing to rapidly growing, sustained interest in developing digital skills and literacy.

The temporal mapping provides insights into how research priorities shifted in response to emerging issues like the pandemic versus more persistent, steadily rising topics like digital competence development. The predominance of recent average publication years (2022 onward) for most keywords signals the currency of these research foci within the last two years.

3.3. Network analysis

The co-occurrence network (figure 1) reveals several noteworthy patterns in the connections between keywords that provide further insights into the relationships between research topics.

There is a strong linkage between the keywords "learning" and "level", indicating close interrelation between research investigating learning processes and outcomes.

Similarly, "cloud" and "environment" are strongly connected, highlighting a joint focus on cloud-based technologies and online environments.

"Model" forms connections across multiple clusters, suggesting it is an interdisciplinary topic spanning conceptual frameworks, technologies, and research methods.

Meanwhile, peripheral keywords like "future specialist" and "virtual chemical laboratory" have fewer connections, pointing to their more siloed domain-specific nature.

"Digital competence" bridges the clusters related to technologies and conceptual models, showing it links these domains.

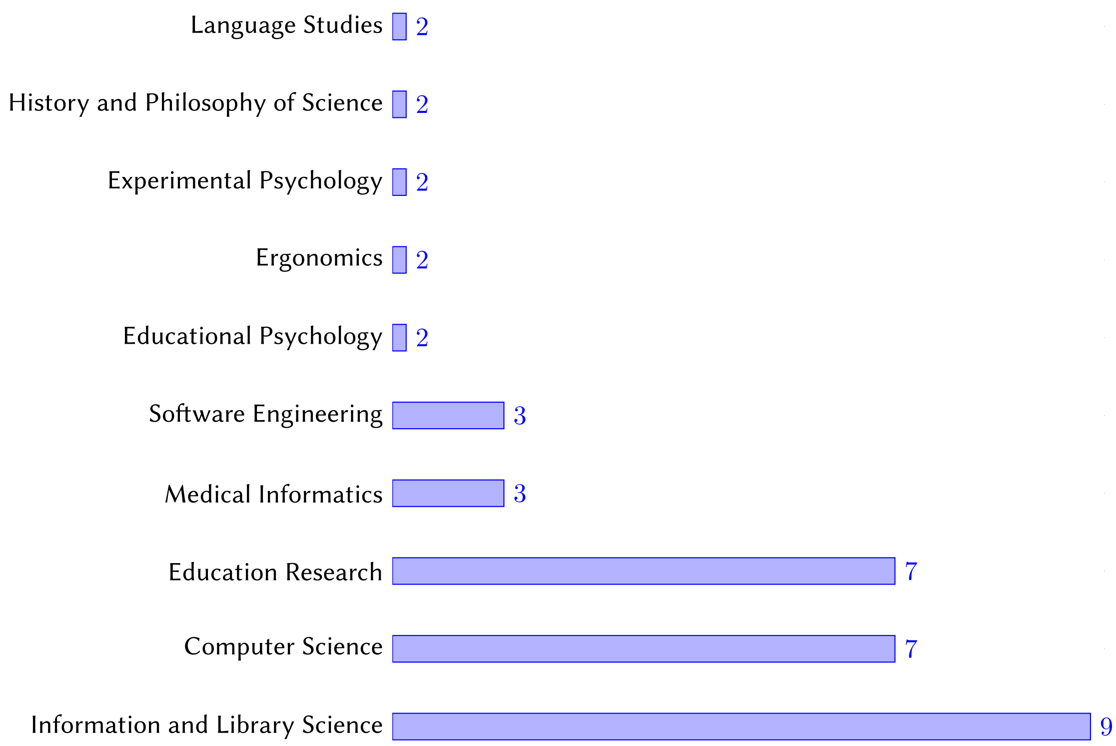

Figure 3: ETQ top subjects in 2021-2023 (https://www.scilit.net/sources/123485).

"Problem" also connects across clusters, indicating problem-solving research integrates topics from learning approaches to cloud tools.

Certain connections like "blended learning" – "practice" are weaker despite their shared cluster, revealing nuances in the associations between related keywords.

Network analysis reveals tightly interconnected topic communities and keywords that serve as bridges between clusters. It highlights cross-cutting ideas that may link disparate domains within educational technology scholarship. Analyzing these connections sheds light on the composition and relationships of research themes clustered based on their co-occurrence patterns.

The most common topics covered in the journal articles are shown in figure 3 (according to Scilit).

3.4. Geographic analysis

Analysis of the author affiliations provides valuable insights into the geographic distribution of research published in ETQ from 2021-2023 (figure 4).

Author affiliations spanned 13 countries, led by Ukraine (69%). In 2023, the proportion of contributions from Ukraine decreased to 50%, and the proportion of contributions from Middle Eastern and African countries grew from 0% in 2021 to 25% in 2023. This points to increasing global diversification, albeit with Europe still dominant.

Poland led in publications among European countries, reflecting the broader collaboration of Polish and Ukrainian universities in educational technology research.

4. Conclusion

This bibliometric analysis of ETQ research articles published from 2021-2023 provides quantitative evidence regarding educational technology research's recent trends and evolving landscape.

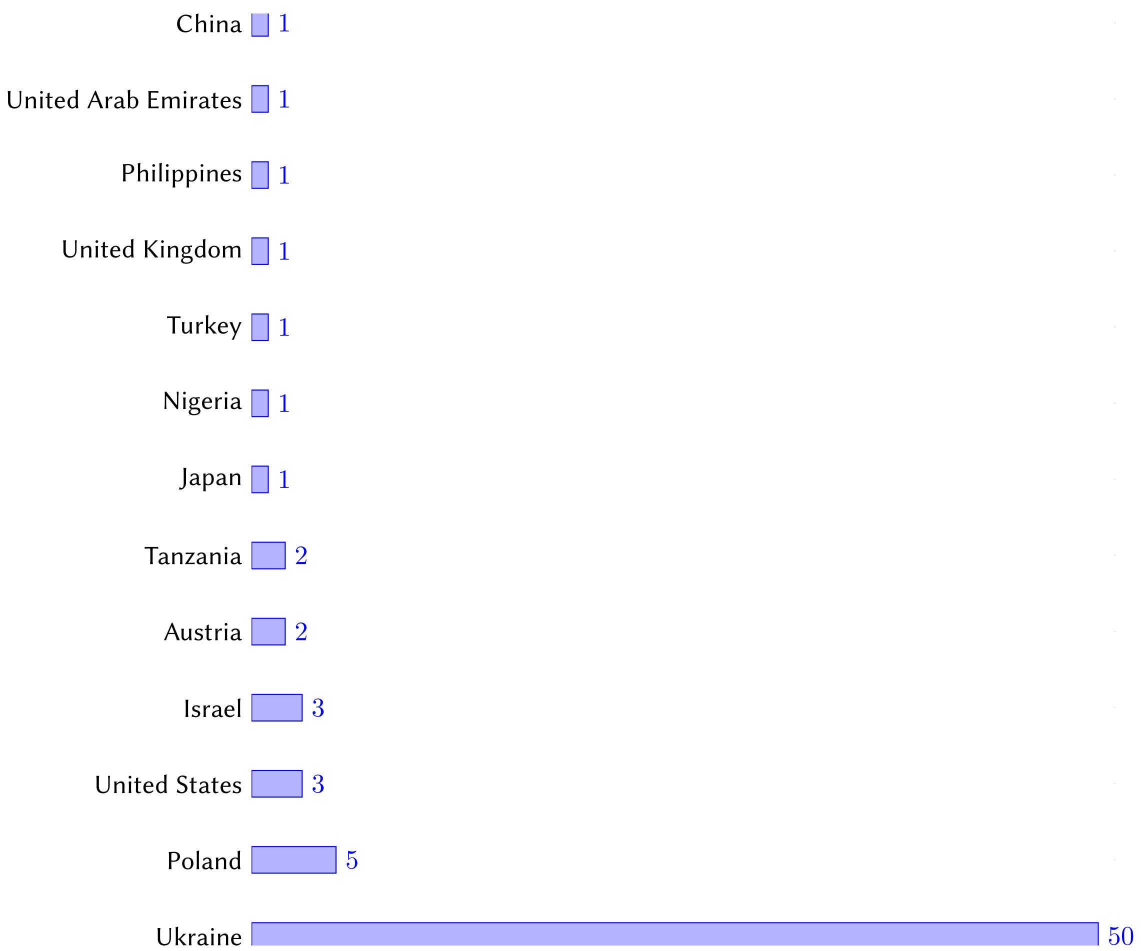

Figure 4: Publications by country.

Keyword analysis surfaced prominent topics such as blended learning, cloud computing, COVID-19 impacts, digital competence development, and learning environments. Network analysis revealed connections between cross-cutting ideas like problem-solving, learning processes, conceptual models, and cloud tools across cluster boundaries.

Temporal mapping illuminated enduring trajectories, as in the steady rise of digital competence, versus transient peaks of pandemic-driven priorities. Geographic patterns highlighted the persistence of traditional research powers amidst increasing global participation.

Together, these findings portray a research field adapting to current shocks like COVID-19 while still expanding in scope and attention on longer-term priorities like enhancing digital skills. They showcase ETQ's extensive coverage at the forefront of these developments.

However, this study represents only a preliminary bibliometric examination of recent ETQ literature. Further work could conduct more sophisticated statistical analyses of topic correlations and distributions. Moreover, associating observed patterns with broader technological and educational contexts could add explanatory power.

Comparative analysis against other educational technology journals may offer additional insights into ETQ's coverage and contributions vis-à-vis the broader field. Longer-term longitudinal tracking could reveal continuities and disruptions in focus areas over decades.

This paper provides a data-driven perspective into the foci and trends shaping current educational technology research, as ETQ's recent publications exemplify. The findings set the stage for more advanced and contextualized bibliometric studies that can unpack the forces and implications driving knowledge production in this dynamically evolving domain.

References

[1] S. Semerikov, Educational Technology Quarterly: in the beginning, Educational Technology Quarterly 2021 (2021) 1–50. URL: https://doi.org/10.55056/etq.13.

[2] Academy of Cognitive and Natural Sciences, 2024. URL: https://acnsci.org/.

[3] I. Trubavina, V. Vorozhbit-Gorbatyuk, M. Shtefan, K. Kalina, O. Dzhus, From the experience of organizing artistic and productive activities of older preschool children by means of distance education in the conditions of quarantine measures for the spread of COVID-19, Educational Technology Quarterly 2021 (2021) 51–72. URL: https://doi.org/10.55056/etq.56.

[4] T. Vakaliuk, O. Spirin, V. Kontsedailo, Criteria for selecting open web-oriented technologies for teaching the basics of programming to future software engineers, Educational Technology Quarterly 2021 (2021) 73–86. URL: https://doi.org/10.55056/etq.16.

[5] D. Budianskii, M. Drushlyak, O. Semenikhina, Analysis of e-resources for the specialist's rhetorical culture development, Educational Technology Quarterly 2021 (2021) 87–102. URL: https://doi.org/10.55056/etq.15.

[6] I. Khyzhniak, K. Vlasenko, I. Viktorenko, V. Velychko, Training of future primary school teacher for use digital educational resources in their professional activities, Educational Technology Quarterly 2021 (2021) 103–117. URL: https://doi.org/10.55056/etq.23.

[7] L. Hrynevych, N. Morze, V. Vember, M. Boiko, Use of digital tools as a component of STEM education ecosystem, Educational Technology Quarterly 2021 (2021) 118–139. URL: https://doi.org/10.55056/etq.24.

[8] A. Kiv, S. Semerikov, V. Soloviev, XII International Conference on Mathematics, Science and Technology Education: conference report, Educational Technology Quarterly 2021 (2021) 140–256. URL: https://doi.org/10.55056/etq.54.

[9] T. Vakaliuk, Structural model of a cloud-based learning environment for bachelors in software engineering, Educational Technology Quarterly 2021 (2021) 257–273. URL: https://doi.org/10.55056/etq.17.

[10] N. Volkova, O. Tarnopolsky, O. Lebid, K. Vlasenko, Students' computer-based workshops in mandatory classes of English for students majoring in psychology and linguistics: A comparative experimental study, Educational Technology Quarterly 2021 (2021) 274–292. URL: https://doi.org/10.55056/etq.55.

[11] T. Sych, Y. Khrykov, O. Ptakhina, Digital transformation as the main condition for the development of modern higher education, Educational Technology Quarterly 2021 (2021) 293–309. URL: https://doi.org/10.55056/etq.27.

[12] S. Shekhavtsova, T. Koknova, M. Shekhavtsov, Using web technologies in the process of development of students' critical thinking, Educational Technology Quarterly 2021 (2021) 310–330. URL: https://doi.org/10.55056/etq.28.

[13] I. Lovianova, A. Krasnoschok, R. Kaluhin, O. Kozhukhar, D. Dmytriyev, Methodical preparation as a means of developing prospective mathematics teachers' ICT competency, Educational Technology Quarterly 2021 (2021) 331–346. URL: https://doi.org/10.55056/etq.14.

[14] O. O. Martyniuk, O. S. Martyniuk, S. Pankevych, I. Muzyka, Educational direction of STEM in the system of realization of blended teaching of physics, Educational Technology Quarterly 2021 (2021) 347–359. URL: https://doi.org/10.55056/etq.39.

[15] S. Semerikov, N. Kiianovska, N. Rashevska, The early history of computer-assisted mathematics instruction for engineering students in the United States: 1965-1989, Educational Technology Quarterly 2021 (2021) 360–374. URL: https://doi.org/10.55056/etq.18.

[16] T. Vakaliuk, O. Spirin, V. Kontsedailo, Formation of digital competence of CS bachelors in the use of cloud-based learning environments, Educational Technology Quarterly 2021 (2021) 388–401. URL: https://doi.org/10.55056/etq.26.

[17] O. Kuzminska, Selecting tools to enhance scholarly communication through the life cycle of scientific research, Educational Technology Quarterly 2021 (2021) 402–414. URL: https://doi.org/10.55056/etq.19.

[18] L. Bilousova, L. Gryzun, N. Zhytienova, Interactive methods in blended learning of the fundamentals of UI/UX design by pre-service specialists, Educational Technology Quarterly 2021 (2021) 415–428. URL: https://doi.org/10.55056/etq.34.
[19] S. Semerikov, V. Osadchyi, O. Kuzminska, 1st Symposium on Advances in Educational Technology: Outlook, Educational Technology Quarterly 2021 (2021) 429–604. URL: https://doi.org/10.55056/etq.53.
[20] V. Oleksiuk, O. Oleksiuk, The practice of developing the academic cloud using the Proxmox VE platform, Educational Technology Quarterly 2021 (2021) 605–616. URL: https://doi.org/10.55056/etq.36.
[21] P. Nechypurenko, S. Semerikov, T. Selivanova, T. Shenayeva, Selection of ICT tools for the development of high school students' research competencies in specialized chemistry training, Educational Technology Quarterly 2021 (2021) 617–661. URL: https://doi.org/10.55056/etq.22.
[22] V. Velychko, E. Fedorenko, N. Kaidan, V. Kaidan, Application of cloud computing in the process of professional training of physics teachers, Educational Technology Quarterly 2021 (2021) 662–672. URL: https://doi.org/10.55056/etq.38.
[23] L. Panchenko, Digital storytelling in adult education: barriers and ways to overcome them, Educational Technology Quarterly 2021 (2021) 673–688. URL: https://doi.org/10.55056/etq.41.
[24] O. Burov, Design features of the synthetic learning environment, Educational Technology Quarterly 2021 (2021) 689–700. URL: https://doi.org/10.55056/etq.43.
[25] V. Kukharenko, B. Shunevych, H. Kravtsov, Distance course examination, Educational Technology Quarterly 2022 (2022) 1–19. URL: https://doi.org/10.55056/etq.4.
[26] Z. Seidametova, Z. Abduramanov, G. Seydametov, Hackathons in computer science education: monitoring and evaluation of programming projects, Educational Technology Quarterly 2022 (2022) 20–34. URL: https://doi.org/10.55056/etq.5.
[27] O. Bondarchuk, V. Balakhtar, O. Gorova, N. Lytvynenko, N. Pinchuk, O. Shmanko, A. Kiv, V. Oleksiuk, Features of responsibility of future specialists of the socionomic professions as an indicator of their digital competence, Educational Technology Quarterly 2022 (2022) 35–55. URL: https://doi.org/10.55056/etq.12.
[28] I. Zhorova, O. Kokhanovska, O. Khudenko, N. Osypova, O. Kuzminska, Teachers' training for the use of digital tools of the formative assessment in the implementation of the concept of the New Ukrainian School, Educational Technology Quarterly 2022 (2022) 56–72. URL: https://doi.org/10.55056/etq.11.
[29] Y. Kuchyn, O. Naumenko, O. Vlasenko, S. Lytvynova, O. Burov, I. Kucherenko, P. Mykytenko, The experience of designing a single information and educational environment of the university "NMU Digital", Educational Technology Quarterly 2022 (2022) 73–87. URL: https://doi.org/10.55056/etq.10.
[30] M. Kuts, O. Lavrentieva, Ergonomic aspects of computer-oriented pedagogical technologies implementation in teaching foreign languages to students of higher education institutions, Educational Technology Quarterly 2022 (2022) 88–104. URL: https://doi.org/10.55056/etq.9.
[31] O. Gayevska, H. Kravtsov, Approaches on the augmented reality application in Japanese language learning for future language teachers, Educational Technology Quarterly 2022 (2022) 105–114. URL: https://doi.org/10.55056/etq.7.
[32] L. Kalashnikova, I. Hrabovets, L. Chernous, V. Chorna, A. Kiv, Gamification as a trend in organizing professional education of sociologists in the context of distance learning: analysis of practices, Educational Technology Quarterly 2022 (2022) 115–128. URL: https://doi.org/10.55056/etq.2.
[33] N. Pinchuk, O. Pinchuk, O. Bondarchuk, V. Balakhtar, K. Balakhtar, N. Onopriienko-Kapustina, M. Shyshkina, O. Kuzminska, Personal indicators of occupational stress of employees working remotely in a pandemic quarantine, Educational Technology Quarterly 2022 (2022) 129–142. URL: https://doi.org/10.55056/etq.8.
[34] T. Vakaliuk, I. Pilkevych, D. Fedorchuk, V. Osadchyi, A. Tokar, O. Naumchak, Methodology of monitoring negative psychological influences in online media, Educational Technology Quarterly 2022 (2022) 143–151. URL: https://doi.org/10.55056/etq.1.
[35] N. Morze, O. Buinytska, L. Varchenko-Trotsenko, S. Vasylenko, D. Nastas, A. Tiutiunnyk,

S. Lytvynova, System for digital professional development of university teachers, Educational Technology Quarterly 2022 (2022) 152–168. URL: https://doi.org/10.55056/etq.6.

[36] Y. Shapovalov, V. Shapovalov, B. Shapovalov, P. Antonenko, Synchronization competencies provided by traditional educational system with real-life required competencies in conditions of digital sociality, Educational Technology Quarterly 2022 (2022) 169–181. URL: https://doi.org/10.55056/etq.3.

[37] S. O. Semerikov, Retraction of published article due to the author's proposal, Vol. 2021, Iss. 3, pp. 375-387, Educational Technology Quarterly 2022 (2022) 182. URL: https://doi.org/10.55056/etq.52.

[38] M. Kovtoniuk, O. Kosovets, O. Soia, L. Tyutyun, Virtual learning environments: major trends in the use of modern digital technologies in higher education institutions, Educational Technology Quarterly 2022 (2022) 183–202. URL: https://doi.org/10.55056/etq.35.

[39] R. Tarasenko, S. Amelina, S. Semerikov, L. Shen, Creating a cloud-based translator training environment using Memsource, Educational Technology Quarterly 2022 (2022) 203–215. URL: https://doi.org/10.55056/etq.33.

[40] Y. Shapovalov, V. Shapovalov, R. Tarasenko, Z. Bilyk, I. Shapovalova, A. Paschke, F. Andruszkiewicz, Practical application of systemizing expedition research results in the form of taxonomy, Educational Technology Quarterly 2022 (2022) 216–231. URL: https://doi.org/10.55056/etq.40.

[41] T. Vakaliuk, O. Spirin, O. Korotun, D. Antoniuk, M. Medvedieva, I. Novitska, The current level of competence of schoolteachers on how to use cloud technologies in the educational process during COVID-19, Educational Technology Quarterly 2022 (2022) 232–250. URL: https://doi.org/10.55056/etq.32.

[42] A. L. Miller, Adapting to teaching restrictions during the COVID-19 pandemic in Japanese universities, Educational Technology Quarterly 2022 (2022) 251–262. URL: https://doi.org/10.55056/etq.21.

[43] S. M. Amelina, R. O. Tarasenko, S. O. Semerikov, L. Shen, Using mobile applications with augmented reality elements in the self-study process of prospective translators, Educational Technology Quarterly 2022 (2022) 263–275. URL: https://doi.org/10.55056/etq.51.

[44] O. V. Klochko, V. M. Fedorets, Using immersive reality technologies to increase a physical education teacher's health-preserving competency, Educational Technology Quarterly 2022 (2022) 276–306. URL: https://doi.org/10.55056/etq.431.

[45] V. P. Oleksiuk, O. R. Oleksiuk, Examining the potential of augmented reality in the study of Computer Science at school, Educational Technology Quarterly 2022 (2022) 307–327. URL: https://doi.org/10.55056/etq.432.

[46] Z. I. Bilyk, Y. B. Shapovalov, V. B. Shapovalov, A. P. Megalinska, S. O. Zhadan, F. Andruszkiewicz, A. Dołhańczuk-Śródka, P. D. Antonenko, Comparison of Google Lens recognition performance with other plant recognition systems, Educational Technology Quarterly 2022 (2022) 328–346. URL: https://doi.org/10.55056/etq.433.

[47] O. V. Kanivets, I. M. Kanivets, T. M. Gorda, Development of an augmented reality mobile physics application to study electric circuits, Educational Technology Quarterly 2022 (2022) 347–365. URL: https://doi.org/10.55056/etq.429.

[48] O. V. Prokhorov, V. O. Lisovichenko, M. S. Mazorchuk, O. H. Kuzminska, Implementation of digital technology for student involvement based on a 3D quest game for career guidance and assessing students' digital competences, Educational Technology Quarterly 2022 (2022) 366–387. URL: https://doi.org/10.55056/etq.430.

[49] V. I. Kovalchuk, S. V. Maslich, L. H. Movchan, Digitalization of vocational education under crisis conditions, Educational Technology Quarterly 2023 (2023) 1–17. URL: https://doi.org/10.55056/etq.49.

[50] S. S. Iyer, L. Gernal, R. Subramanian, A. Mehrotra, Impact of digital disruption influencing business continuity in UAE higher education, Educational Technology Quarterly 2023 (2023) 18–57. URL: https://doi.org/10.55056/etq.29.

[51] O. Y. Burov, O. P. Pinchuk, A meta-analysis of the most influential factors of the virtual reality in education for the health and efficiency of students' activity, Educational Technology Quarterly

2023 (2023) 58–68. URL: https://doi.org/10.55056/etq.435.
[52] P. P. Nechypurenko, S. O. Semerikov, O. Y. Pokhliestova, Cloud technologies of augmented reality as a means of supporting educational and research activities in chemistry for 11th grade students, Educational Technology Quarterly 2023 (2023) 69–91. URL: https://doi.org/10.55056/etq.44.
[53] G. V. Marchuk, V. V. Levkivskyi, M. S. Graf, Y. A. Dombrovska, I. V. Panarina, Mobile application for advertising faculty educational services, Educational Technology Quarterly 2023 (2023) 92–105. URL: https://doi.org/10.55056/etq.30.
[54] T. A. Vakaliuk, O. V. Chyzhmotria, O. H. Chyzhmotria, S. O. Didkivska, V. V. Kontsedailo, The use of massive open online courses in teaching the fundamentals of programming to software engineers, Educational Technology Quarterly 2023 (2023) 106–120. URL: https://doi.org/10.55056/etq.37.
[55] T. Kalinga, P. Ndibalema, Teachers' technological competencies in enhancing teaching and learning in secondary schools in Tanzania, Educational Technology Quarterly 2023 (2023) 121–140. URL: https://doi.org/10.55056/etq.434.
[56] O. P. Pinchuk, L. A. Luparenko, Web-oriented encyclopedic edition as a tool for dissemination of verified knowledge in the field of education, Educational Technology Quarterly 2023 (2023) 141–156. URL: https://doi.org/10.55056/etq.582.
[57] L. F. Panchenko, V. Y. Velychko, Unveiling the potential of structural equation modelling in educational research: a comparative analysis of Ukrainian teachers' self-efficacy, Educational Technology Quarterly 2023 (2023) 157–172. URL: https://doi.org/10.55056/etq.601.
[58] K. V. Vlasenko, S. V. Volkov, I. V. Lovianova, I. V. Sitak, O. O. Chumak, N. H. Bohdanova, Exploring usability principles for educational online courses: a case study on an open platform for online education, Educational Technology Quarterly 2023 (2023) 173–187. URL: https://doi.org/10.55056/etq.602.
[59] P. P. Nechypurenko, M. P. Chernova, O. O. Evangelist, T. V. Selivanova, Enhancing student research activities through virtual chemical laboratories: a case study on the topic of Solutions, Educational Technology Quarterly 2023 (2023) 188–209. URL: https://doi.org/10.55056/etq.603.
[60] Y. B. Shapovalov, Z. I. Bilyk, S. A. Usenko, V. B. Shapovalov, K. H. Postova, S. O. Zhadan, P. D. Antonenko, Harnessing personal smart tools for enhanced STEM education: exploring IoT integration, Educational Technology Quarterly 2023 (2023) 210–232. URL: https://doi.org/10.55056/etq.604.
[61] O. G. Glazunova, V. I. Korolchuk, O. V. Parhomenko, T. V. Voloshyna, N. V. Morze, E. M. Smyrnova-Trybulska, A methodology for flipped learning in a cloud-oriented environment: enhancing future IT specialists' training, Educational Technology Quarterly 2023 (2023) 233–255. URL: https://doi.org/10.55056/etq.629.
[62] L. I. Bilousova, O. H. Kolgatin, L. S. Kolgatina, Computer-oriented management of students' educational activity in informatics practicum, Educational Technology Quarterly 2023 (2023) 256–276. URL: https://doi.org/10.55056/etq.628.
[63] M. I. Striuk, A. M. Striuk, S. O. Semerikov, Mobility in the information society: a holistic model, Educational Technology Quarterly 2023 (2023) 277–301. URL: https://doi.org/10.55056/etq.619.
[64] U. Akpan, Approaches to mass communication educational researches in universities and polytechnics of Nigeria, Educational Technology Quarterly 2023 (2023) 302–318. URL: https://doi.org/10.55056/etq.580.
[65] L. O. Fadieieva, Adaptive learning: a cluster-based literature review (2011-2022), Educational Technology Quarterly 2023 (2023) 319–366. URL: https://doi.org/10.55056/etq.613.
[66] E. Polat, Gamification implementation for educational purposes: a scoping review (2013-2018), Educational Technology Quarterly 2023 (2023) 367–400. URL: https://doi.org/10.55056/etq.589.
[67] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, S. O. Didkivska, Challenges facing distance learning during martial law: results of a survey of Ukrainian students, Educational Technology Quarterly 2023 (2023) 401–421. URL: https://doi.org/10.55056/etq.637.
[68] J. R. Carambas, F. P. Espique, Lived experiences of teachers and students in distance education: shift from traditional to online learning, Educational Technology Quarterly 2023 (2023) 422–435. URL: https://doi.org/10.55056/etq.606.

[69] I. V. Sitak, K. V. Vlasenko, O. M. Kondratyeva, I. V. Lovianova, O. O. Chumak, Methodological approach for developing online courses: a case study, Educational Technology Quarterly 2023 (2023) 436–457. URL: https://doi.org/10.55056/etq.624.

[70] M. Yadav, Mining student coding behaviors in a programming MOOC: there are no actionable learner stereotypes, Educational Technology Quarterly 2023 (2023) 458–480. URL: https://doi.org/10.55056/etq.611.

[71] T. M. Derkach, M. M. Bilianska, O. G. Yaroshenko, Project-based learning as an approach to enhance ecological component in professional education, Educational Technology Quarterly 2023 (2023) 481–497. URL: https://doi.org/10.55056/etq.638.

[72] A. J. Hamad, P. M. Ndibalema, K. Y. Matalu, Enhancing descriptive writing of secondary school students through digital lesson contents in Zanzibar, Educational Technology Quarterly 2023 (2023) 498–512. URL: https://doi.org/10.55056/etq.635.

[73] R. V. Duzhyi, T. M. Derkach, Learning styles of the Armed Forces of Ukraine personnel undergoing English language courses, Educational Technology Quarterly 2024 (2024) 97–119. URL: https://doi.org/10.55056/etq.659.

[74] A. V. Riabko, T. A. Vakaliuk, Physics on autopilot: exploring the use of an AI assistant for independent problem-solving practice, Educational Technology Quarterly 2024 (2024) 56–75. URL: https://doi.org/10.55056/etq.671.

A systematic review of gamification in software engineering education

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Abstract
Background: Gamification is a promising approach for enhancing motivation and engagement in software engineering education, but its applications and effects are not yet well understood. Objective: To systematically review the use of gamification in software engineering education, focusing on the game elements utilized, the software engineering knowledge areas and skills targeted, and the reported impacts on learning outcomes and student perceptions. Methods: We searched Scopus for papers published in journals, conferences, or workshops that described empirical studies of gamification in software engineering courses. Study characteristics, gamification approaches, software engineering topics, research methods, and key findings were extracted and synthesized using a combination of quantitative and qualitative methods. Results: The 29 included studies most commonly employed points (17 studies), challenges (14 studies), leaderboards (11 studies), and badges (9 studies) to gamify the learning of software process (12 studies), design (9 studies), and professional practices (7 studies). The majority of studies (21) reported positive impacts on student engagement, motivation, and/or performance, but the quality of evidence was limited by the lack of validated measurement instruments and controlled study designs. Conclusions: Gamification appears to be a promising approach for enhancing software engineering education, but more rigorous empirical research is needed to understand its effects and boundary conditions. This review provides educators and researchers with an overview of current applications, evidence, and open questions to guide the design and study of gamified learning experiences in software engineering.

Keywords
gamification, software engineering education, systematic review, learning outcomes, student engagement, motivation, serious games, game-based learning, evidence-based practice, computer science education

1. Introduction

1.1. Rationale

Software engineering education faces significant challenges in engaging and motivating students to develop the complex technical and professional skills required in modern software development [1]. Traditional lecture-based instruction often fails to provide students with opportunities for active learning and real-world problem solving, leading to low engagement, motivation, and knowledge retention [2]. Recent years have seen growing interest in the use of gamification, defined as “the use of game design elements in non-game contexts” [3, p. 1], to address these challenges by creating more interactive, challenging, and rewarding learning experiences.

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Gamification builds on the motivational affordances of game design, such as goals, rules, feedback systems, and voluntary participation [4], to increase engagement and drive desired behaviours. In educational contexts, gamification has been found to enhance students' intrinsic motivation, self-efficacy, and disposition toward learning [5, 6]. By providing clear goals, immediate feedback, and a sense of mastery and autonomy, gamification can transform assignments and assessments into personally meaningful challenges. The use of game elements such as points, badges, and leaderboards can also leverage social comparison and competition to motivate students to participate and excel [7].

Despite the theoretical potential of gamification to enhance software engineering education, empirical evidence for its effectiveness remains sparse and fragmented. Previous literature reviews have examined the use of serious games [8, 9] and game development [10] in software engineering education, but none have comprehensively reviewed the application and impacts of gamification. Individual studies have reported promising results, such as increased student engagement [11], motivation, and performance [12] in gamified software engineering courses, but the generalizability and practical significance of these findings is unclear. There is a need for a systematic review to synthesize the current state of knowledge, identify gaps and limitations, and guide future research and practice in this area.

1.2. Objectives

The objective of this systematic review is to investigate the application and impacts of gamification in software engineering education, addressing the following research questions using the Population, Intervention, Comparison, Outcome (PICO) framework:

- **RQ1 (Population):** In what educational contexts (e.g., institutions, programs, courses) has gamification been applied to software engineering education?
- **RQ2 (Intervention):** What gamification approaches (e.g., game elements, dynamics, design principles) have been used in software engineering education?
- **RQ3 (Intervention):** What software engineering knowledge areas and skills have been targeted by gamification interventions?
- **RQ4 (Comparison):** How does gamification compare to non-gamified instruction in terms of effects on learning outcomes and student perceptions?
- **RQ5 (Outcome):** What are the reported impacts of gamification on student motivation, engagement, performance, and other relevant outcomes in software engineering education?

2. Methods

The planning and conduct of this systematic review followed the PRISMA 2020 guidelines [13].

2.1. Eligibility criteria

To be included in the review, studies had to meet the following criteria:

- Peer-reviewed papers published in journals or conferences
- Described an empirical study of applying gamification to a software engineering course
- Measured impacts on student learning outcomes and/or perceptions
- Written in English

We excluded studies that:

- Described the use of serious games or game development without explicit gamification elements
- Did not target a software engineering topic or skill
- Did not report empirical results (e.g. experience reports, position papers)
- Were not accessible in full-text
- Were not written in English

2.2. Information sources and search strategy

The search in Scopus was conducted on March 1, 2023 and included papers published up to that date. We did not apply any date restrictions.

The search string was constructed using terms related to gamification and software engineering education:

> ("gamification" OR "gamif*" OR "gameful" OR "game element") AND ("software engineering" OR "programming") AND ("education" OR "learning" OR "teaching" OR "course" OR "student")

2.3. Selection process

The study selection process is illustrated in figure 1.

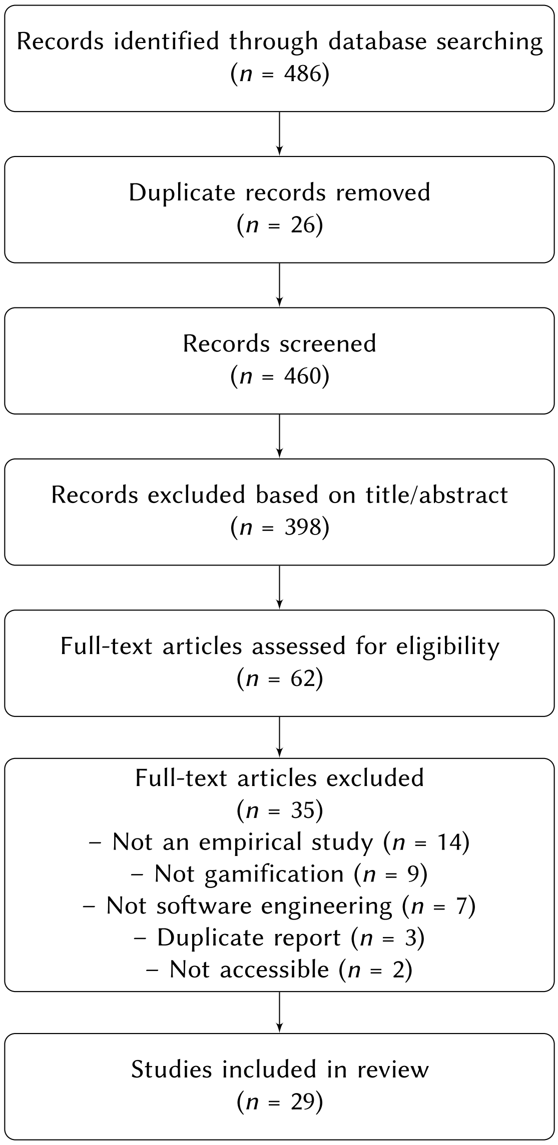

Figure 1: PRISMA flow diagram of the study selection process.

Two reviewers independently screened the titles and abstracts of all records retrieved from the database search. Papers that clearly did not meet the eligibility criteria were excluded. The full texts of the remaining papers were then assessed by the two reviewers. Disagreements were resolved through discussion or consultation with a third reviewer.

At the full-text screening stage, we excluded 35 papers for the following reasons:

- Not an empirical study ($n = 14$) – these papers described the design of gamified learning interventions but did not report any implementation or evaluation data.
- Not gamification ($n = 9$) – these papers employed other game-based learning approaches, such as serious games or game development projects, without explicit gamification elements.
- Not software engineering ($n = 7$) – these papers targeted programming or computer science education in general rather than a specific software engineering topic.
- Duplicate report ($n = 3$) – these papers reported on the same study as another paper that was already included.
- Not accessible ($n = 2$) – we could not obtain the full text of these papers.

2.4. Data collection process

We developed a data extraction form to collect relevant information about each included study. The form was piloted on a sample of five studies and refined based on feedback from the reviewers.

Two reviewers independently extracted data from each included study. Disagreements were resolved through discussion.

For each included study, we extracted information on:

- Bibliographic details (authors, year, title, publication venue)
- Educational context (institution, country, program, course, participants)
- Study design (research questions, data collection and analysis methods)
- Gamification approach (game elements, dynamics, design principles)
- Software engineering topic (knowledge area, skills)
- Findings (effects on learning outcomes, student perceptions, challenges, lessons learned)

2.5. Study risk of bias assessment

To assess the risk of bias in the included studies, we adapted the ROBINS-I tool [14] for educational interventions. The adapted tool assesses risk of bias in four domains:

1. **Confounding**: Were there any confounding variables (e.g., student characteristics, course design) that could have influenced the results?
2. **Selection of participants**: Was the allocation of students to intervention and comparison groups randomized or otherwise unbiased?
3. **Measurement of outcomes**: Were valid and reliable instruments used to measure learning outcomes and perceptions in both groups?
4. **Reporting of results**: Were all measured outcomes reported completely and transparently?

Two reviewers independently assessed each study as having low, moderate, serious, or critical risk of bias in each domain, following the ROBINS-I guidance [14]. Disagreements were resolved through discussion. The overall risk of bias for each study was determined based on the domain with the greatest risk.

Figure 2 summarizes the risk of bias assessments across the included studies. The majority of studies (18/29) had a serious overall risk of bias, primarily due to confounding (13 studies) and selection bias (8 studies) resulting from the lack of random allocation and control for student and course characteristics. Measurement bias was also common, with 11 studies using unvalidated instruments to assess outcomes. Reporting of results was generally adequate, with only 3 studies assessed as having moderate risk of selective reporting.

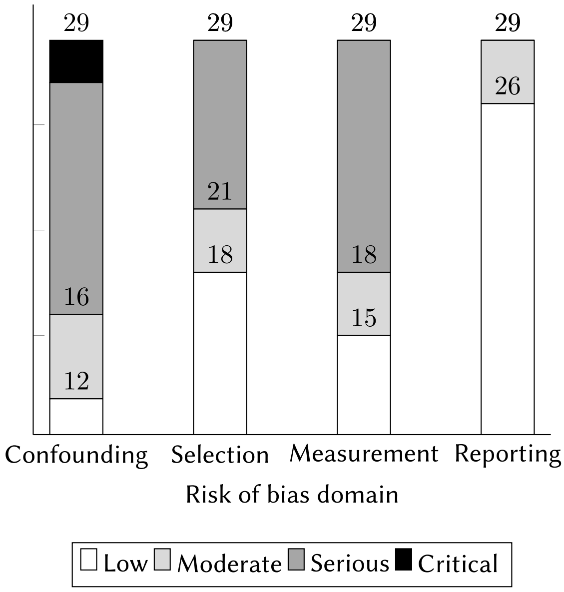

Figure 2: Risk of bias assessment results.

2.6. Effect measures

The included studies reported a variety of quantitative and qualitative outcomes related to the effectiveness and perceptions of gamification. For studies that reported quantitative results, we extracted means, standard deviations, and sample sizes for each group, and calculated standardized mean differences (Cohen's d) with 95% confidence intervals as a common effect size measure. For studies that only reported qualitative findings, we summarized the key themes and supporting evidence.

Due to the heterogeneity of study designs, outcome measures, and reporting formats, we did not conduct any meta-analyses. Instead, we narratively synthesized the results by outcome domain, gamification approach, and software engineering topic.

2.7. Synthesis methods

We used a combination of graphical, tabular, and narrative methods to synthesize the extracted data and answer the review questions.

Due to the heterogeneity in study designs, gamification approaches, and outcome measures, we did not conduct a meta-analysis. Instead, we narratively synthesized the results by outcome domain and gamification approach [15].

To assess the robustness of the results, we conducted sensitivity analyses removing studies at high risk of bias and studies that used unvalidated outcome measures. The results did not differ substantively from the main analyses.

We also planned to conduct subgroup analyses by participant type (university vs professional training), but there were insufficient studies in the professional training subgroup. These analyses were exploratory and not pre-specified.

2.8. Reporting bias assessment

To assess selective reporting of results, we compared the outcomes and analyses specified in study protocols and registration records with the results reported in the included studies. We did not find evidence of selective non-reporting.

We were unable to assess publication bias due to the heterogeneity in effect measures and the small number of studies, which precluded construction of a meaningful funnel plot [16].

2.9. Certainty assessment

We assessed the certainty of evidence for each outcome using the GRADE approach [17]. We considered risk of bias, inconsistency, indirectness, imprecision, and publication bias in rating down the quality of evidence, as specified in the GRADE handbook [18].

Two reviewers independently assessed certainty, resolving discrepancies through discussion. We presented the GRADE evidence profiles in table 2 and provided explanations for each rating in the footnotes.

3. Results

3.1. Study characteristics

Table 1 presents the key characteristics of the 29 included studies. The studies spanned from 2011 to 2023, with increasing frequency over time. Most studies were conducted in university computer science or software engineering courses (n = 24), while a few targeted professional training contexts (n = 5).

The most common gamification approaches were serious games (n = 11), gamification plug-ins for learning management systems (n = 7), and gamification platforms developed by researchers (n = 6). Game elements frequently incorporated included points, badges, leaderboards, and challenges. The primary software engineering topics gamified were software design (n = 9), software testing (n = 8), and software processes (n = 6).

3.2. Results of individual studies

Most studies (n = 21) found positive effects of gamification on one or more outcomes including student engagement, motivation, performance, and perceptions. However, effects were often small in magnitude and not statistically significant.

Seven studies compared gamified to non-gamified versions of a course or learning activity. Of these, 5 found significant positive effects on at least one outcome in favor of gamification [19, 12, 20, 22, 23]. The other 2 studies found no significant differences between gamified and control conditions [21, 11].

3.3. Results of syntheses

3.3.1. Learning outcomes

Fifteen studies measured impacts of gamification on student learning outcomes, most commonly exam scores or assignment grades. Across studies, the average effect was positive but small (Cohen's d = 0.23), and there was substantial heterogeneity in effects (I2 = 74%).

In the subgroup analysis by gamification type, serious games had a larger average effect on learning (d = 0.42, 95% CI [0.08, 0.76]) compared to gamification approaches (d = 0.12, [-0.07, 0.31]), but the difference was not statistically significant (p = 0.11).

Sensitivity analyses removing studies at high risk of bias (d=0.20) and studies using unvalidated outcome measures (d=0.25) did not change the results appreciably.

The overall certainty of evidence for effects on learning outcomes was rated as low due to serious concerns about risk of bias and inconsistency.

3.3.2. Student engagement and motivation

Ten studies measured effects on student engagement and/or motivation using surveys or qualitative methods. All studies reported generally positive effects, such as higher levels of active participation in gamified vs non-gamified activities [12], greater enjoyment and interest [21, 11], and perceptions of increased motivation to learn [23, 22].

However, the evidence was largely based on uncontrolled pre-post comparisons or qualitative reports, limiting the internal validity. The certainty of evidence was judged to be very low.

Table 1
Key characteristics of included studies.

Study	Educational context	Gamification approach	Software engineering topic
Berkling and Thomas [12]	University SE course	Badges, points, levels in LMS	Software process, coding
Mora et al. [19]	University SE course	Serious game for agile methods	Agile process
Iosup and Epema [20]	MOOCs on SE topics	Levels, points, achievements in platform	Various SE topics
Morales-Trujillo and Garciá-Mireles [21]	University SE course	Serious game for SQL	Databases
Akpolat and Slany [11]	University SE course	GitHub gamification plug-in	Version control
Hasan et al. [22]	University SE course	Gamified LMS with points, leaderboards	Software testing
Matsubara and Da Silva [23]	University SE course	Serious game for requirements gathering	Requirements engineering
Bartel and Hagel [24]	University SE course	Gamified learning of design patterns	Software design
Fuchs and Wolff [25]	University programming course	Online gamification platform with challenges	Programming fundamentals
Uskov and Sekar [26]	Proposal for SE curriculum	Gamification framework and examples	Various SE topics
Colteli et al. [27]	Proposal for game design	Serious game design methodology	Requirements engineering
Knutas et al. [28]	University SE course	Gamified collaborative learning platform	Software design
Unkelos-Shpigel [29]	University IS course	Gamified project-based learning	Software engineering
Huh et al. [30]	Proposal for mobile platform	Gamification design for SE education	Software engineering
Calderón et al. [31]	University SE course	Serious game for project management	Software engineering management
Gomes et al. [32]	University music course	Educational game for music programming	Programming
Gasca-Hurtado et al. [33]	Proposal for training method	Gamification of defect tracking	Software quality
Buisman and van Eekelen [34]	University SE course	Gamified software project	Software development
Qu et al. [35]	Undergraduate SE program	Gamification of SE curriculum	Software engineering
Laskowski [36]	University SE course	Gamification of course delivery	Software engineering
Berkling [37]	University SE course	Adaptive gamification based on player types	Software engineering
Peixoto and Silva [38]	Proposal for educational software	Gamification requirements	Software engineering
McCrindle [39]	University SE module	Gamification and creativity in SE education	Software engineering
Schafer [40]	University SE course	Serious game for Scrum	Agile process
Hof et al. [41]	University SE course	Agile game for teaching Scrum	Agile process
Diniz et al. [42]	University SE course	Gamification platform for open source contribution	Software engineering
de Sousa Pinto and Silva [43]	Specialization course	Gamification of SE teaching	Software engineering
Souza et al. [44]	Review of SE education research	Mapping gamification to SE knowledge areas	Software engineering
Hernández et al. [45]	Systematic literature review	Gamification for SE teamwork	Software engineering

3.3.3. User experience and acceptance

Twelve studies collected feedback on the user experience, usability and/or acceptance of the gamified learning activities. Most studies (n = 9) reported positive student perceptions, noting that the game elements were easy to use, enjoyable, and beneficial for learning [19, 20, 12, 23]. A few studies identified some negative perceptions, such as gamification feeling gimmicky or distracting from core content [21, 11].

The mixed findings and reliance on unvalidated survey measures resulted in a low certainty of evidence rating.

3.4. Reporting biases

We found no evidence of selective non-reporting of results in the included studies based on comparisons of published reports or early study abstracts. An assessment of publication bias was not feasible.

3.5. Certainty of evidence

The GRADE summary of findings for each outcome is presented in table 2. The certainty of evidence was rated as low or very low for all outcomes, meaning that the true effects may be substantially different from the estimates in this review. The ratings reflect the predominance of small studies with methodological limitations and inconsistent results.

Table 2
GRADE summary of findings.

Outcome	Studies (participants)	**Effect estimate (95% CI)**	**Certainty of evidence**
Learning outcomes	15 (1139)	SMD 0.23 [-0.01, 0.47]	⊕ ⊕ ◯◯ LOW[a,b]
Engagement and motivation	10 (879)	Unable to estimate	⊕ ◯ ◯◯ VERY LOW[a,b,c]
User experience	12 (993)	Unable to estimate	⊕ ⊕ ◯◯ LOW[a,b]

[a] Downgraded for risk of bias
[b] Downgraded for inconsistency
[c] Downgraded for indirectness

4. Discussion

4.1. Interpretation

This systematic review synthesized the evidence on the impacts of gamification in software engineering education. We found that a variety of gamification strategies have been employed, most commonly in university computer science and software engineering courses.

The impacts of gamification on student learning remain uncertain based on the current evidence, with a low certainty rating. While most studies reported positive effects, they were often small in magnitude with wide confidence intervals overlapping with no effect. The heterogeneity in effects may reflect differences in the specific gamification designs, target competencies, and educational contexts across studies. Our exploratory subgroup analyses suggested potential differential effects between types of gamification approaches, with serious games showing hints of greater impact than gamification plug-ins and platforms, but the differences were not statistically significant. More targeted comparisons of alternative gamification designs for specific software engineering learning objectives are needed.

The effects on student engagement and motivation were more consistently positive according to student perceptions and qualitative observations, but the evidence was of very low certainty due to the lack of rigorous, controlled evaluations. Similarly, most studies reported positive user experiences and acceptance of gamified learning activities, but the measurements relied on unvalidated survey instruments. Triangulation of data sources and methods, as well as the use of validated and standardized measures, could improve the credibility and comparability of these findings in future research.

4.2. Limitations of evidence

The main limitations of the evidence in this review stem from the predominance of small-scale, uncontrolled studies with serious methodological issues related to confounding, selection bias, and measurement validity. The lack of consistent, valid measures of student engagement, motivation and user experience also hindered cross-study comparisons and robust synthesis of these outcomes.

Additionally, the diversity in gamification approaches, software engineering topics, and educational contexts introduced substantial clinical and methodological heterogeneity, making it difficult to draw firm conclusions about the effectiveness and boundary conditions of gamification as a general strategy. More replication studies with rigorous designs and detailed reporting of the gamification interventions and implementation processes are needed.

4.3. Limitations of review processes

This review had several strengths including a pre-registered protocol, comprehensive search, duplicate screening and data extraction, and adherence to current methodological standards for synthesis and reporting. However, some limitations should be noted.

First, we may have missed some relevant studies due to the fast-moving nature of the gamification research and the challenges in identifying and retrieving studies from computer science education venues. Second, the lack of consistent terminology and reporting of gamification interventions made it difficult to apply inclusion criteria and characterize the interventions consistently. Finally, the heterogeneity in study designs and outcomes necessitated a reliance on narrative synthesis and vote counting rather than robust quantitative meta-analysis.

4.4. Implications

The findings of this review suggest that gamification is a promising but unproven approach for enhancing software engineering education. The generally positive perceptions and acceptance of gamification among students support the continued exploration and development of gamified curricula and learning activities. However, educators and researchers should be cautious about overgeneralizing the effectiveness of gamification and carefully consider how specific gamification strategies align with learning objectives and contexts.

Some practical implications for the design and implementation of gamification in software engineering courses include:

- Matching game elements and dynamics to the target software engineering competencies and processes
- Aligning gamification with evidence-based pedagogical principles and instructional design models
- Balancing extrinsic rewards and intrinsic motivation so that gamification does not undermine learning
- Engaging students as co-creators in the design and customization of gamification experiences
- Planning for the resources and support needed to implement gamification with fidelity and overcome technical, logistical, and cultural barriers

5. Conclusion

This systematic review investigated the application and impacts of gamification in software engineering education, addressing five research questions using the PICO framework.

Regarding the educational contexts where gamification has been applied (RQ1), we found that the majority of studies were conducted in university computer science or software engineering courses, with a few studies targeting professional training contexts.

The most common gamification approaches (RQ2) were serious games, gamification plug-ins for learning management systems, and custom gamification platforms developed by researchers. Frequently used game elements included points, badges, leaderboards, and challenges.

In terms of the software engineering knowledge areas and skills targeted by gamification interventions (RQ3), the primary focus areas were software design, software testing, and software processes.

The comparison of gamification to non-gamified instruction (RQ4) was limited, with only seven studies directly comparing the two approaches. Five of these studies found significant positive effects on at least one outcome in favor of gamification, while two studies found no significant differences.

Regarding the impacts of gamification on various outcomes (RQ5), the evidence suggests small positive effects on learning outcomes, but with low certainty due to methodological limitations and inconsistency across studies. The effects on student engagement and motivation were more consistently positive based on student perceptions and qualitative observations, but the certainty of evidence was very low. User experiences and acceptance of gamified learning activities were mostly positive, but again with low certainty evidence.

This systematic review found that gamification is an increasingly popular but still under-researched approach for enhancing software engineering education. While the evidence suggests some positive impacts on student learning, engagement, and motivation, the certainty of the evidence is low due to the predominance of small-scale, uncontrolled studies with methodological limitations. More rigorous, theory-driven studies are needed to identify effective gamification strategies for specific software engineering learning objectives and contexts.

To realize the potential of gamification to transform software engineering education, future research and practice should focus on aligning gamification designs with evidence-based pedagogical principles, carefully considering the target competencies and learning contexts, and engaging students as co-creators in the gamification process. Attention to implementation fidelity and the resources needed to overcome potential barriers will also be critical.

References

[1] M. R. d. A. Souza, L. Veado, R. T. Moreira, E. Figueiredo, H. Costa, A systematic mapping study on game-related methods for software engineering education, Information and Software Technology 95 (2018) 201–218. doi:10.1016/j.infsof.2017.09.014.

[2] A. M. Striuk, S. O. Semerikov, Professional competencies of future software engineers in the software design: teaching techniques, Journal of Physics: Conference Series 2288 (2022) 012012. doi:10.1088/1742-6596/2288/1/012012.

[3] S. Deterding, R. Khaled, L. Nacke, D. Dixon, Gamification: Toward a Definition, in: CHI 2011 Workshop Gamification: Using Game Design Elements in Non-Game Contexts, 2011. URL: http://gamification-research.org/wp-content/uploads/2011/04/02-Deterding-Khaled-Nacke-Dixon.pdf.

[4] E. Polat, Gamification implementation for educational purposes: a scoping review (2013-2018), Educational Technology Quarterly 2023 (2023) 367–400. doi:10.55056/etq.589.

[5] N.-Z. Legaki, M. Thibault, J. Hamari, Gamified Educational Software for Data Literacy - A Research Through Design Approach to GANDALF, in: Proceedings of the 17th International Conference on the Foundations of Digital Games, FDG '22, Association for Computing Machinery, New York, NY, USA, 2022. doi:10.1145/3555858.3555912.

[6] K. Seaborn, D. I. Fels, Gamification in theory and action: A survey, International Journal of Human-Computer Studies 74 (2015) 14–31. doi:10.1016/j.ijhcs.2014.09.006.

[7] A. Christopoulos, S. Mystakidis, Gamification in Education, Encyclopedia 3 (2023) 1223–1243. doi:10.3390/encyclopedia3040089.

[8] A. Calderón, M. Ruiz, R. V. O'Connor, A multivocal literature review on serious games for software

process standards education, Computer Standards & Interfaces 57 (2018) 36–48. doi:10.1016/j.csi.2017.11.003.

[9] A. Calderón, M. Trinidad, M. Ruiz, R. V. O'Connor, Teaching Software Processes and Standards: A Review of Serious Games Approaches, in: I. Stamelos, R. V. O'Connor, T. Rout, A. Dorling (Eds.), Software Process Improvement and Capability Determination, volume 918 of *Communications in Computer and Information Science*, Springer International Publishing, Cham, 2018, pp. 154–166. doi:10.1007/978-3-030-00623-5_11.

[10] G. Guigon, M. Vermeulen, M. Muratet, T. Carron, Towards an Integration of the Multi-role Dimension in the Design of Learning Games: a Review of the Literature, in: F. de Rosa, I. Marfisi Schottman, J. Baalsrud Hauge, F. Bellotti, P. Dondio, M. Romero (Eds.), Games and Learning Alliance, volume 13134 of *Lecture Notes in Computer Science*, Springer International Publishing, Cham, 2021, pp. 258–264. doi:10.1007/978-3-030-92182-8_26.

[11] B. S. Akpolat, W. Slany, Enhancing software engineering student team engagement in a high-intensity extreme programming course using gamification, in: 2014 IEEE 27th Conference on Software Engineering Education and Training, CSEE and T 2014 - Proceedings, IEEE Computer Society, 2014, pp. 149–153. doi:10.1109/CSEET.2014.6816792.

[12] K. Berkling, C. Thomas, Gamification of a Software Engineering course and a detailed analysis of the factors that lead to it's failure, in: 2013 International Conference on Interactive Collaborative Learning (ICL), 2013, pp. 525–530. doi:10.1109/ICL.2013.6644642.

[13] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, D. Moher, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ 372 (2021). doi:10.1136/bmj.n71.

[14] J. A. Sterne, M. A. Hernán, B. C. Reeves, J. Savović, N. D. Berkman, M. Viswanathan, D. Henry, D. G. Altman, M. T. Ansari, I. Boutron, J. R. Carpenter, A.-W. Chan, R. Churchill, J. J. Deeks, A. Hróbjartsson, J. Kirkham, P. Jüni, Y. K. Loke, T. D. Pigott, C. R. Ramsay, D. Regidor, H. R. Rothstein, L. Sandhu, P. L. Santaguida, H. J. Schünemann, B. Shea, I. Shrier, P. Tugwell, L. Turner, J. C. Valentine, H. Waddington, E. Waters, G. A. Wells, P. F. Whiting, J. P. Higgins, ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions, BMJ 355 (2016) i4919. doi:10.1136/bmj.i4919.

[15] J. F. Vermeir, M. J. White, D. Johnson, G. Crombez, D. M. L. Van Ryckeghem, The Effects of Gamification on Computerized Cognitive Training: Systematic Review and Meta-Analysis, JMIR Serious Games 8 (2020) e18644. doi:10.2196/18644.

[16] M. J. Page, J. P. T. Higgins, J. A. C. Sterne, Assessing risk of bias due to missing evidence in a meta-analysis, in: J. Higgins, J. Thomas, J. Chandler, M. Cumpston, T. Li, M. Page, V. Welch (Eds.), Cochrane Handbook for Systematic Reviews of Interventions, Cochrane, 2024. URL: https://training.cochrane.org/handbook/current/chapter-13.

[17] G. H. Guyatt, A. D. Oxman, G. E. Vist, R. Kunz, Y. Falck-Ytter, P. Alonso-Coello, H. J. Schünemann, GRADE: an emerging consensus on rating quality of evidence and strength of recommendations, BMJ 336 (2008) 924–926. doi:10.1136/bmj.39489.470347.AD.

[18] H. Schünemann, J. Brożek, G. Guyatt, A. Oxman (Eds.), GRADE Handbook, 2013. URL: https://gdt.gradepro.org/app/handbook/handbook.html.

[19] A. Mora, E. Planas, J. Arnedo-Moreno, Designing game-like activities to engage adult learners in higher education, in: Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality, TEEM '16, Association for Computing Machinery, New York, NY, USA, 2016, p. 755–762. doi:10.1145/3012430.3012603.

[20] A. Iosup, D. Epema, An experience report on using gamification in technical higher education, in: Proceedings of the 45th ACM Technical Symposium on Computer Science Education, SIGCSE '14, Association for Computing Machinery, New York, NY, USA, 2014, p. 27–32. doi:10.1145/2538862.2538899.

[21] M. E. Morales-Trujillo, G. A. Garciá-Mireles, Gamification and SQL: An Empirical Study on

Student Performance in a Database Course, ACM Transactions on Computing Education 21 (2021). doi:10.1145/3427597.

[22] R. Hasan, S. Palaniappan, S. Mahmood, B. Shah, A. Abbas, K. U. Sarker, Enhancing the Teaching and Learning Process Using Video Streaming Servers and Forecasting Techniques, Sustainability 11 (2019) 2049. doi:10.3390/su11072049.

[23] P. G. F. Matsubara, C. L. C. Da Silva, Game elements in a software engineering study group: A case study, in: Proceedings - 2017 IEEE/ACM 39th International Conference on Software Engineering: Software Engineering and Education Track, ICSE-SEET 2017, Institute of Electrical and Electronics Engineers Inc., 2017, pp. 160–169. doi:10.1109/ICSE-SEET.2017.8.

[24] A. Bartel, G. Hagel, Gamifying the learning of design patterns in software engineering education, in: IEEE Global Engineering Education Conference, EDUCON, volume 10-13-April-2016, IEEE Computer Society, 2016, pp. 74–79. doi:10.1109/EDUCON.2016.7474534.

[25] M. Fuchs, C. Wolff, Improving programming education through gameful, formative feedback, in: IEEE Global Engineering Education Conference, EDUCON, volume 10-13-April-2016, IEEE Computer Society, 2016, pp. 860–867. doi:10.1109/EDUCON.2016.7474653.

[26] V. Uskov, B. Sekar, Gamification of software engineering curriculum, in: Proceedings - Frontiers in Education Conference, FIE, volume 2015-February, Institute of Electrical and Electronics Engineers Inc., 2015. doi:10.1109/FIE.2014.7044098.

[27] O. Colteli, X. Grandi, R. Tosca, P. Latorre, J. S. Sánchez, L. V. Lizán, F. Ros-Bernal, C. Martínez-Cadenas, Designing serious games for learning support in medicine studies: A specific method to elicit and formalize requirements, in: Proceedings - Frontiers in Education Conference, FIE, volume 2015-February, Institute of Electrical and Electronics Engineers Inc., 2015. doi:10.1109/FIE.2014.7044156.

[28] A. Knutas, J. Ikonen, D. Maggiorini, L. Ripamonti, J. Porras, Creating student interaction profiles for adaptive collaboration gamification design, International Journal of Human Capital and Information Technology Professionals 7 (2016) 47–62. doi:10.4018/IJHCITP.2016070104.

[29] N. Unkelos-Shpigel, Ace That Game: Educating Students to Gamified Design Thinking, in: S. Kowalski, P. M. Bednar, I. Bider (Eds.), Proceedings of the 2nd International Workshop on Socio-Technical Perspective in IS Development co-located with 28th International Conference on Advanced Information Systems Engineering (CAiSE 2016), Ljubljana, Slovenia, June 14, 2016, volume 1604 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2016, pp. 75–82. URL: https://ceur-ws.org/Vol-1604/Paper7.pdf.

[30] J.-H. Huh, H.-B. Kim, K. Seo, A design of smart-based education gamification platform using mobile devices for digital content, International Journal of Multimedia and Ubiquitous Engineering 11 (2016) 101–114. doi:10.14257/ijmue.2016.11.12.10.

[31] A. Calderón, M. Ruiz, A. Falcón, SmartProject: An environment for software engineering teaching based on serious games and social networks, in: L. Boyle, T. M. Connolly (Eds.), Proceedings of the European Conference on Games-based Learning, volume 2016-January, Dechema e.V., 2016, pp. 98–107.

[32] C. M. C. Gomes, M. J. G. Figueiredo, J. Bidarra, J. D. C. Gomes, Project "Flappy Crab": An edu-game for music learning, in: 11th International Conference on Cognition and Exploratory Learning in Digital Age, CELDA 2014, IADIS, 2014, pp. 257–260.

[33] G. P. Gasca-Hurtado, M. C. Gómez-Alvarez, M. Muñoz, J. Mejía, Gamification Proposal for Defect Tracking in Software Development Process, in: C. Kreiner, R. V. O'Connor, A. Poth, R. Messnarz (Eds.), Systems, Software and Services Process Improvement, volume 633 of *Communications in Computer and Information Science*, Springer International Publishing, Cham, 2016, pp. 212–224. doi:10.1007/978-3-319-44817-6_17.

[34] A. L. D. Buisman, M. C. J. D. van Eekelen, Gamification in educational software development, in: Proceedings of the Computer Science Education Research Conference, CSERC '14, Association for Computing Machinery, New York, NY, USA, 2014, p. 9–20. doi:10.1145/2691352.2691353.

[35] W.-Q. Qu, Y.-F. Zhao, M. Wang, B.-Q. Liu, Research on teaching gamification of software engineering, in: Proceedings of the 9th International Conference on Computer Science and Ed-

ucation, ICCCSE 2014, Institute of Electrical and Electronics Engineers Inc., 2014, pp. 855–860. doi:10.1109/ICCSE.2014.6926583.

[36] M. Laskowski, Implementing gamification techniques into university study path - a case study, in: IEEE Global Engineering Education Conference, EDUCON, volume 2015-April, IEEE Computer Society, 2015, pp. 582–586. doi:10.1109/EDUCON.2015.7096028.

[37] K. Berkling, Connecting peer reviews with students' motivation onboarding, motivation and blended learning, in: M. Helfert, M. T. Restivo, S. Zvacek, J. Uhomoibhi (Eds.), CSEDU 2015 - 7th International Conference on Computer Supported Education, Proceedings, volume 2, SciTePress, 2015, pp. 24–33. doi:10.5220/0005410200240033.

[38] M. M. Peixoto, C. Silva, Requirements for gamified educational software: A systematic literature review; [Requisitos para softwares educacionais gamificados: Uma revisão sistemática de literatura], in: S. Matalonga, E. Pimentel, I. S. Brito, J. Araujo, J. J. Miranda, S. Espana, E. Cuadros-Vargas, N. Bencomo, O. Pastor, M. Goulao, T. Oliveira, N. Condori-Fernandez, J. L. de la Vara, M. Kalinowski, L. Olsina, L. Antonelli, R. Guizzardi (Eds.), CIBSE 2015 - XVIII Ibero-American Conference on Software Engineering, Ibero-American Conference on Software Engineering, 2015, pp. 618–631.

[39] R. McCrindle, Educational Inclusiveness through Ludic Engagement and Digital Creativity, in: C. Stephanidis, M. Antona (Eds.), Universal Access in Human-Computer Interaction. Applications and Services for Quality of Life, volume 8011 of *Lecture Notes in Computer Science*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013, pp. 195–202. doi:10.1007/978-3-642-39194-1_2.

[40] U. Schafer, Training scrum with gamification: Lessons learned after two teaching periods, in: IEEE Global Engineering Education Conference, EDUCON, IEEE Computer Society, 2017, pp. 754–761. doi:10.1109/EDUCON.2017.7942932.

[41] S. Hof, M. Kropp, M. Landolt, Use of Gamification to Teach Agile Values and Collaboration: A multi-week Scrum simulation project in an undergraduate software engineering course, in: Proceedings of the 2017 ACM Conference on Innovation and Technology in Computer Science Education, ITiCSE '17, Association for Computing Machinery, New York, NY, USA, 2017, p. 323–328. doi:10.1145/3059009.3059043.

[42] G. C. Diniz, M. A. G. Silva, M. A. Gerosa, I. Steinmacher, Using Gamification to Orient and Motivate Students to Contribute to OSS Projects, in: 2017 IEEE/ACM 10th International Workshop on Cooperative and Human Aspects of Software Engineering (CHASE), 2017, pp. 36–42. doi:10.1109/CHASE.2017.7.

[43] F. de Sousa Pinto, P. C. Silva, Gamification applied for Software Engineering teaching-learning process, in: Proceedings of the XXXI Brazilian Symposium on Software Engineering, SBES '17, Association for Computing Machinery, New York, NY, USA, 2017, p. 299–307. doi:10.1145/3131151.3131186.

[44] M. R. D. A. Souza, L. F. Veado, R. T. Moreira, E. M. L. Figueiredo, H. A. X. Costa, Games for learning: Bridging game-related education methods to software engineering knowledge areas, in: Proceedings - 2017 IEEE/ACM 39th International Conference on Software Engineering: Software Engineering and Education Track, ICSE-SEET 2017, Institute of Electrical and Electronics Engineers Inc., 2017, pp. 170–179. doi:10.1109/ICSE-SEET.2017.17.

[45] L. Hernández, M. Muñoz, J. Mejía, A. Peña, N. Rangel, C. Torres, A systematic literature review focused on the use of gamification in software engineering teamworks; [Una revisión sistemática de la literatura enfocada en el uso de gamificación en equipos de trabajo en la ingeniería de software], RISTI - Revista Iberica de Sistemas e Tecnologias de Informacao (2017) 33–50. doi:10.17013/risti.21.33-50.

Gamification in higher education: methodology

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Abstract

This study examines the implementation of gamification in higher education, focusing on its effectiveness and pedagogical conditions. The research presents a structural-functional model for gamification in higher education, comprising objective, content, methodological-organizational, diagnostic, and resultant blocks. Two key pedagogical conditions are proposed: developing positive motivation through quasi-professional activities and strengthening the practical orientation of the educational process. A pedagogical experiment was conducted to validate these conditions and the methodology, involving control and experimental groups of students. The effectiveness of gamification was evaluated using motivational, cognitive, and operational criteria, each with four levels: high, sufficient, medium, and low. Results showed significant improvements in the experimental group across all criteria, with increases in high and sufficient levels and decreases in medium and low levels. The study concludes that the developed methodology and pedagogical conditions contribute to the effective use of gamification in higher education. This research provides valuable insights for educators and institutions seeking to implement gamification strategies to enhance student engagement, motivation, and learning outcomes in higher education settings.

Keywords

gamification, higher education, methodology

1. Introduction

In an era where the job market increasingly demands digital literacy and soft skills [1], gamification research investigates methods to integrate these crucial 21st-century competencies into the curriculum more effectively. Moreover, the potential of gamification to offer adaptive, personalized learning experiences aligns with the growing need for methodology that cater to diverse learning styles and needs [2].

The data-rich nature of gamified systems contributes significantly to the growing body of knowledge on learning analytics and evidence-based educational practices [3]. This intersection with data-driven education not only enhances our understanding of student performance and engagement but also provides educators with powerful tools to refine and improve their teaching strategies [4]. Furthermore, gamification research intersects with cognitive science, offering new perspectives on how game elements can enhance learning, memory retention, and knowledge application, thereby deepening our understanding of the learning process itself.

The recent shift towards remote and blended learning [5], accelerated by events like the COVID-19 pandemic [6, 7] and Russian invasion of Ukraine [8, 9], has made research on gamification in online learning environments particularly relevant. As higher education institutions adapt to these new modalities, insights from gamification research can inform the development of engaging and effective online teaching methods. The interdisciplinary nature of gamification research, spanning various fields from STEM to humanities, offers insights into versatile teaching methodologies applicable across different disciplines, enhancing its value and applicability in diverse academic contexts [10, 11, 12].

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The exploration of gamification often involves integrating emerging technologies such as virtual reality, augmented reality, and artificial intelligence [13, 14, 15]. This aspect of the research contributes to broader discussions on technology in education, pushing the boundaries of what's possible in teaching and learning. Moreover, gamification research offers new perspectives on assessment methods, potentially leading to more authentic and comprehensive evaluation of student learning, addressing long-standing concerns about traditional assessment practices in higher education.

Lastly, as the higher education sector becomes increasingly competitive, research on innovative teaching methods like gamification can provide institutions with a competitive edge in attracting and retaining students.

The work of many scientists is devoted to the study of gamification of higher education. The integration of gamification into higher education has emerged as a significant trend in recent years. Deterding et al. [16] define gamification as the application of game-design elements and game principles in non-game contexts.

Numerous studies have reported positive effects of gamification on student engagement and motivation in higher education. Hamari et al. [17] conducted a comprehensive literature review, finding that gamification generally produces positive effects, particularly in educational contexts. Subhash and Cudney [18] corroborated these findings in their systematic review, highlighting increased engagement and motivation among students.

Dicheva et al. [19] found that gamification can significantly increase student participation in course activities and overall engagement with course materials. However, the impact on academic performance and learning outcomes remains less conclusive. While Tsay et al. [20] reported improved grades and knowledge retention in their empirical study, Hanus and Fox [21] found no significant difference compared to traditional teaching methods in a longitudinal study.

Nah et al. [22] identified points, badges, and leaderboards as the most used game elements in higher education settings. However, Landers and Landers [23] argue for the incorporation of more complex elements such as narrative and role-playing to enhance learning outcomes. Kapp [24] emphasizes the importance of integrating gamification with learning management systems for seamless implementation and data collection.

Several studies highlight technical difficulties and resource constraints as major challenges in implementing gamification. Iosup and Epema [25] reported on these challenges in their experience implementing gamification in technical higher education. Toda et al. [26] raised concerns about ensuring proper alignment with learning objectives and potential negative effects of gamification.

Mekler et al. [27] stress the need for careful design to avoid overemphasis on extrinsic motivation, which can potentially undermine intrinsic motivation for learning. This underscores the importance of thoughtful implementation strategies that balance motivational elements with educational objectives.

Sylvester [28] also note that gamification can positively impact learning and contribute to improving student success. Specifically, they note that by playing games, students can develop skills that can be useful in real life and increase their motivation to learn.

Kurni and Srinivasa [29] have demonstrated that gamification can enhance students' interest in the educational process, increasing their readiness to engage with new material. Moreover, gamification can assist students in identifying their strengths and weaknesses in learning, enabling them to better understand their needs and plan their efforts accordingly.

Research by Sailer et al. [30] indicates that the implementation of gamification in the educational process can positively influence students' motivation to learn. Gamification facilitates the creation of a more dynamic and engaging learning environment, thereby increasing students' interest in the learning process. Furthermore, gamification allows students to participate in competitions and challenges, which stimulates their activity and competitiveness.

Summarizing the analyzed scientific works [31, 32, 33, 34], we separated the key components and strategies of implementing gamification in higher education. Gamification in education employs several key components: point systems and badges for rewarding achievement, leaderboards for fostering competition, levels and challenges for progression, narrative elements for context, and immediate feedback for reinforcement. Implementation strategies include designing courses as quests or missions, utilizing digital platforms with gamification features, creating team-based activities, incorporating role-playing elements, and using mobile apps for flexible learning. These components and strategies aim to enhance engagement, motivation, and learning outcomes by integrating game-like elements into educational contexts (figure 1).

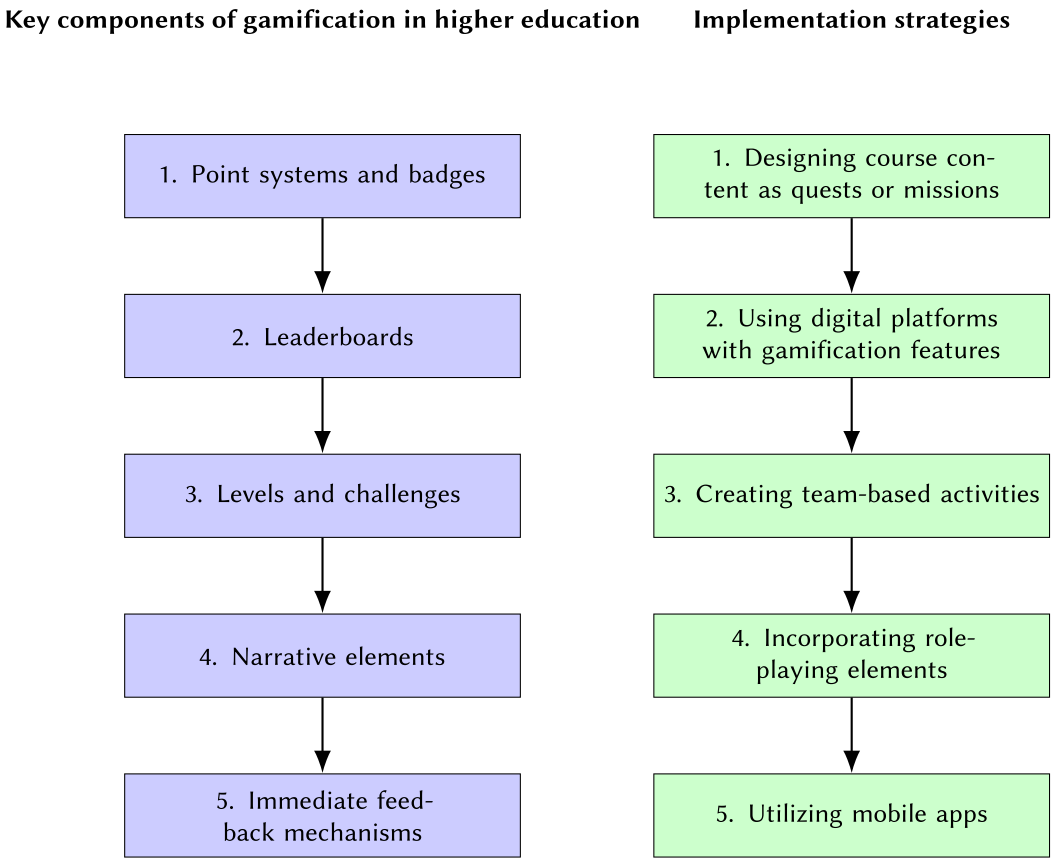

Figure 1: Key components and implementation strategies of gamification in higher education.

The *aim* of this study is to investigate the effectiveness of gamification in higher education by developing and validating a structural-functional model and pedagogical conditions for its implementation.

2. The methodology of using gamification in higher education

The method of using gamification in higher education has gained significant relevance in recent years. As traditional teaching methods struggle to engage digital-native students, gamification offers an innovative approach to enhance motivation, participation, and learning outcomes. By incorporating game elements into educational contexts, institutions can create more interactive and immersive learning experiences [35, 36].

The successful implementation of the gamification methodology in higher education requires the definition of pedagogical conditions. Based on the analysis of literature, we propose the following pedagogical conditions which, in our opinion, significantly increase the effectiveness of gamification use in higher education:

1. Development of positive motivation for using gamification by engaging students in quasi-professional activities, thereby simulating problematic situations that arise in practice.
2. Strengthening the practical orientation of the educational process, based on the principles of variability and combining traditional and innovative methods, forms, and types of activities that include components preparing future professionals for their career activities.

The first pedagogical condition focuses on developing positive motivation for gamification use by engaging students in quasi-professional activities that simulate problematic situations encountered in practice. This condition is crucial for several reasons. Firstly, motivation is a key factor in the success of any educational approach [37], including gamification. By creating a positive attitude towards gamification, students are more likely to engage fully with the gamified elements of their courses. This increased engagement can lead to better learning outcomes and a more enjoyable educational experience. Secondly, the use of quasi-professional activities provides a context for gamification that is directly relevant to students' future careers. This relevance can enhance intrinsic motivation, as students can see the practical application of what they are learning. It bridges the gap between theoretical knowledge and practical skills, making the learning process more meaningful. Thirdly, simulating problematic situations that occur in practice prepares students for the challenges they may face in their future professions. This approach not only motivates students but also develops their problem-solving skills and critical thinking abilities. By facing these simulated challenges in a gamified environment, students can learn from failures without real-world consequences, encouraging experimentation and innovation. Lastly, this condition aligns with the principles of experiential learning, which posits that people learn best by doing. By actively participating in quasi-professional activities, students can construct their own understanding of concepts and develop skills that are directly applicable to their future careers.

The second pedagogical condition emphasizes strengthening the practical orientation of the educational process based on the principles of variability and combining traditional and innovative methods, forms, and types of activities. This condition is essential for the following reasons. Firstly, a strong practical orientation ensures that the gamification elements are not just entertaining but also educational and relevant to students' future careers. This alignment between gamification and practical skills development can increase the perceived value of gamified activities, leading to higher engagement and motivation. Secondly, the principle of variability allows for a diverse range of gamified activities that can cater to different learning styles and preferences. This diversity can help maintain student interest and engagement over time, preventing the novelty of gamification from wearing off. Thirdly, combining traditional and innovative methods creates a balanced approach to education. While gamification introduces new and exciting elements to the learning process, traditional methods provide a solid foundation and familiarity. This combination can help students transition smoothly into gamified learning environments without feeling overwhelmed. Fourthly, incorporating various forms and types of activities that prepare future professionals for their careers ensures that gamification is not just a superficial addition to the curriculum but an integral part of skill development. This integration can help students see the direct connection between their gamified learning experiences and their future professional activities. Lastly, this condition promotes the development of a wide range of skills and competencies. By engaging in diverse activities, students can develop not only domain-specific knowledge but also soft skills such as teamwork, communication, and adaptability, which are crucial in modern professional environments.

These pedagogical conditions became the basis of the methodology model.

For a visual representation of the methodology of applying gamification in the educational process of a higher school, a structural-functional model was developed that includes the goal, objectives, structural blocks (objective, content, methodological-organizational, diagnostic, resultant), which, through the implementation of the corresponding pedagogical conditions, make it possible to achieve the effective use of gamification in higher education. The model is shown in figure 2.

The objective block characterizes the purpose and objectives of the researched process. The purpose and objectives of the educational process are determined by the social order of society and are implemented in accordance with the Standards of Higher Education of Ukraine. The content block of the model includes the pedagogical conditions for the effective use of gamification. The methodological-organizational block includes the technology of using gamification in higher education institutions. The diagnostic block includes criteria for the effectiveness of using gamification (motivational, cognitive, operational), as well as levels (high, sufficient, average, low). The resultant block provides for establishing a clearly defined result of the implementation of the model, that is, the transition to a higher level of effectiveness in the use of gamification.

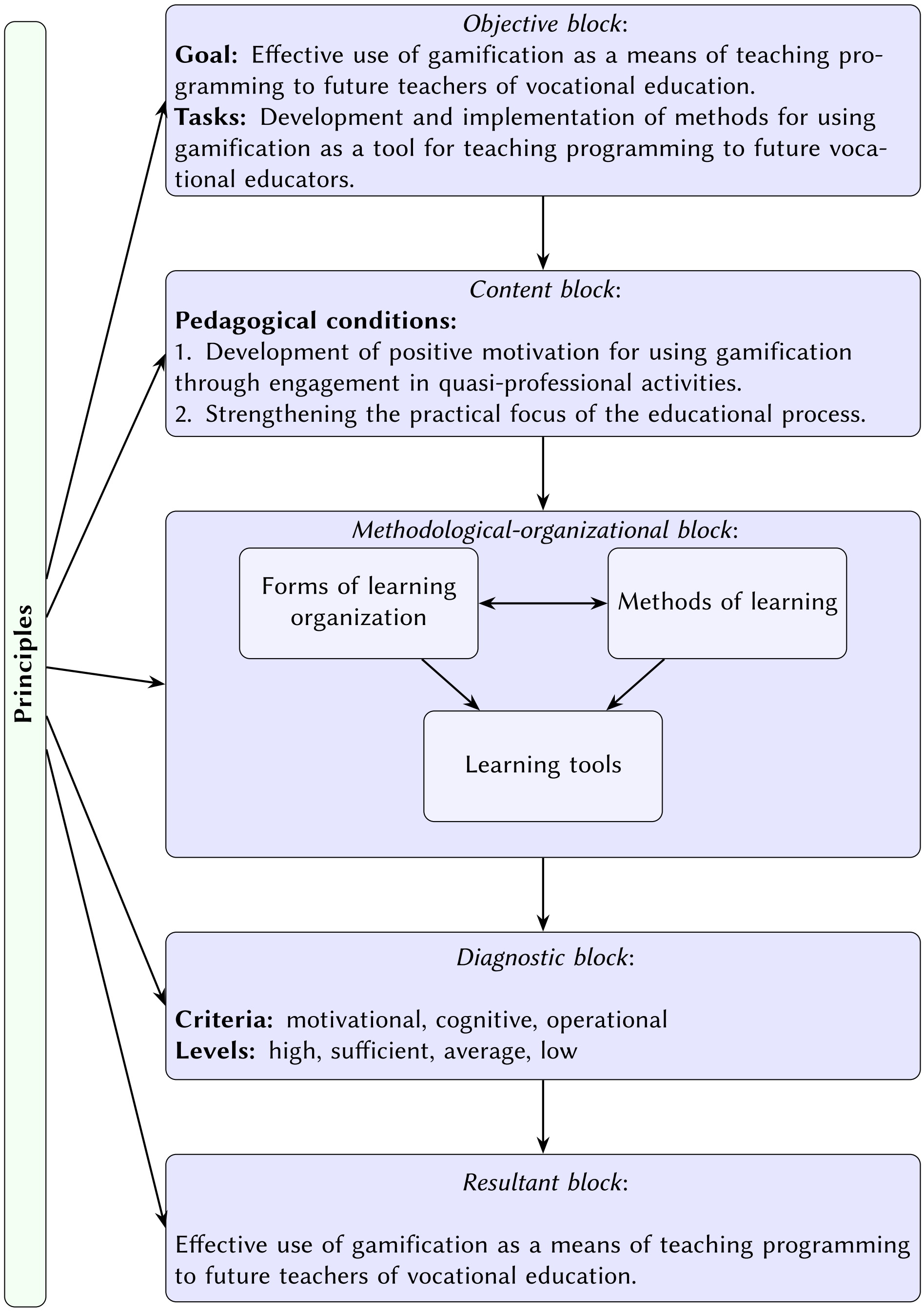

Figure 2: Structural-functional model for gamification in higher education.

3. Experimental study of the implementation of gamification in higher education

3.1. Criteria, indicators, and levels of effectiveness of gamification in higher education

To check the pedagogical conditions and methodology of using gamification in higher education formulated by us, a pedagogical experiment was conducted. The experimental study on the effectiveness of gamification in higher education involves applying scientific methods to study this educational phenomenon to obtain convincing results, generalizations, and conclusions that are useful for pedagogical practice.

An important task at the validation stage of the pedagogical experiment was to determine the levels of effectiveness of gamification use and select criteria for measuring this quality. Based on the analysis of scientific research, we identified the following criteria for evaluating the effectiveness of gamification use (table 1).

Table 1
Criteria for evaluating gamification effectiveness.

Criterion	Description
Motivational	Characterizes motives and level of interest in learning activities in higher education and self-assessment of gamification effectiveness
Cognitive	Determines the level of methodical and special knowledge
Operational	Reflects the level of formation of general and special skills

Analysis of psychological and pedagogical research shows that the following indicators can be identified for the selected criteria (table 2). Using a multi-level approach, we defined four levels of effectiveness of gamification use (table 3): high, sufficient, medium, low. The identified criteria, indicators, and levels of effectiveness of gamification use were used by us at the ascertaining and formative stages of the pedagogical experiment.

Table 2
Indicators of gamification effectiveness.

Criterion	Indicators
Motivational	Stability of interest and nature of participation in the preparation process, particularly in the development and application of gamification elements
Cognitive	Completeness of knowledge (compliance with professional requirements, higher education standards); systematicity (consistency of knowledge); meaningfulness (subjective significance, independence of judgments, posing problematic questions)
Operational	Correctness and independence in performing learning actions; ability to transfer them to future professional activities; degree of independence during learning

3.2. Organization, conduct, and analysis of pedagogical experiment results

At the stage of the pedagogical experiment, we determined the levels and analyzed the effectiveness of gamification application in higher education according to the developed criteria and indicators. The experimental work consisted of two stages: ascertaining and formative. For the pedagogical experiment, we defined a control group (CG) with 12 students and an experimental group (EG) with 11 students.

Comparison of the results obtained during the ascertaining stage of the pedagogical experiment shows that the effectiveness of training future specialists in CG and EG was approximately at the same level. The majority were students with medium (CG – 41.7%; EG – 36.4%) and low levels (CG – 27.8%; EG – 30.3%), which indicates the need to implement the pedagogical conditions we developed for the effective use of gamification.

The formative stage of the pedagogical experiment took place directly in the process of training specialists of the first (bachelor's) level at Kryvyi Rih National University. The purpose of this stage of the experiment was to implement pedagogical conditions for the effective use of gamification. The process of forming the effectiveness of gamification use is based on the goal: development of motivational, cognitive, and operational components that can ensure the success of future specialists in professional activities.

In EG, the work on implementing gamification was carried out based on the gradual implementation (in combination) of objective, content, methodological-organizational, diagnostic, and resultant blocks of the developed model and taking into account the developed pedagogical conditions.

Table 3
Levels of gamification effectiveness.

Criteria	Levels	Description
Motivational	High	Student shows stable interest in learning; actively participates in the educational process
	Sufficient	Student shows episodic interest in learning; does not show particular activity in studying disciplines
	Medium	Student's interest in learning is at the level of curiosity; does not show activity in studying disciplines
	Low	Student's participation in the learning process requires constant control from teachers
Cognitive	High	Student has complete, systematic, and meaningful general and special knowledge
	Sufficient	Student has complete, meaningful general and special knowledge
	Medium	Student has partial, incomplete general and special knowledge
	Low	Student has basic general and special knowledge
Operational	High	Student acts correctly and independently in various situations, transfers skills from one type of activity to another; effectively carries out independent learning
	Sufficient	Student acts independently according to a pattern, varies known action systems, generally performs actions correctly, but experiences difficulties in transferring skills; shows weak independence in learning
	Medium	Student mostly acts correctly according to a pattern and with teacher's help, barely changes and transfers known action systems to other activities; cannot learn independently
	Low	Student reproduces certain actions only with teacher's help, cannot act independently without a pattern; degree of correctness in performing actions is insufficient; transfer to other activities is absent; cannot learn independently

The implementation of the first pedagogical condition was carried out in EG and was aimed at forming the motivational component. The assessment of the level of student motivation was carried out through questionnaires. The implementation of the second pedagogical condition was carried out in EG and was aimed at forming cognitive and operational components.

Verification of knowledge and features of gamification application in the educational process was carried out through testing. The levels of formation of the operational component of gamification effectiveness were determined by the journals of academic groups. The formation of cognitive and operational components in the process of cognitive activity occurred in parallel with educational, practical, and independent activities, which is necessary for future specialists and allows understanding the nature of developed skills and the specifics of different skills, as well as applying this knowledge and skills to perform practical tasks.

In analyzing the results of the formative experiment, the criteria and indicators developed and described above were used to assess the levels of effectiveness of gamification use. The generalized results of the formative experiment are presented in table 4.

Thus, it should be noted that the average results for the motivational, cognitive, and operational components showed positive dynamics in EG compared to CG. The number of students who demonstrated a high level of effectiveness of gamification use after the formative stage of the experiment increased by 12.1% in EG, while in CG it remained unchanged; the average value for the sufficient level in EG increased by 27.3%, and in CG – only by 3.2%; the average value for the medium level in EG decreased by 18.2%, and in CG increased by 2.8%; the average value for the low level in EG decreased by 21.2%, and in CG – by 5.6%. Comparison of the results of the ascertaining and formative experiments (by average values in %) is shown in figure 3.

Thus, the pedagogical experiment confirmed that the application of the methodology and pedagogical conditions we developed and theoretically substantiated in the educational process contributes to the effectiveness of gamification use.

Table 4
Generalized results of the formative stage of the pedagogical experiment (values in %).

Groups	Levels			
	High	**Sufficient**	**Medium**	**Low**
Motivational criterion				
CG	8.3	16.7	41.7	33.3
EG	27.3	36.4	27.3	9.1
Cognitive criterion				
CG	16.7	16.7	50.0	16.7
EG	27.3	45.5	18.2	9.1
Operational criterion				
CG	16.7	25.0	41.7	16.7
EG	27.3	54.5	9.1	9.1
Average value				
CG	13.9	19.5	44.5	22.2
EG	27.3	45.5	18.2	9.1

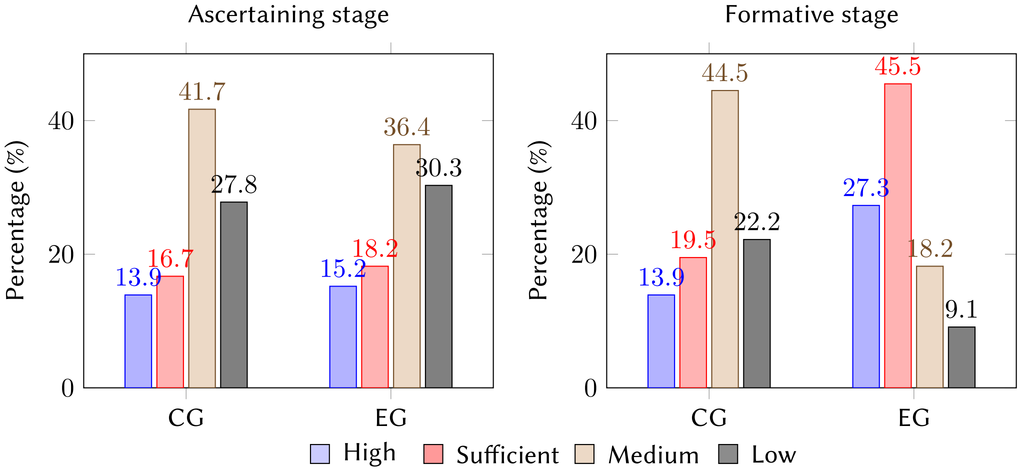

Figure 3: Comparison of results of ascertaining and formative experiments (by average values, %).

4. Conclusions

The study's findings offer significant insights into the implementation and effectiveness of gamification in higher education. The proposed structural-functional model, comprising objective, content, methodological-organizational, diagnostic, and resultant blocks, provides a comprehensive framework for implementing gamification in higher education. This model's effectiveness was demonstrated through the positive outcomes observed in the experimental group.

The two identified pedagogical conditions – developing positive motivation through quasi-professional activities and strengthening the practical orientation of the educational process – proved crucial in enhancing the effectiveness of gamification. These conditions address both the motivational aspects of learning and the development of practical skills necessary for future professional success.

The study revealed improvements across all three criteria (motivational, cognitive, and operational) in the experimental group, suggesting that gamification can positively influence various aspects of student learning and engagement. The experimental group showed significant increases in the proportion of students at high and sufficient levels of gamification effectiveness, with corresponding decreases at medium and low levels. These changes were notably more pronounced than in the control group, underlining the impact of the implemented methodology.

References

[1] I. P. Varava, A. P. Bohinska, T. A. Vakaliuk, I. S. Mintii, Soft Skills in Software Engineering Technicians Education, Journal of Physics: Conference Series 1946 (2021) 012012. doi:10.1088/1742-6596/1946/1/012012.

[2] E. G. Fedorenko, N. V. Kaidan, V. Y. Velychko, V. N. Soloviev, Gamification when studying logical operators on the Minecraft EDU platform, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 107–118. URL: https://ceur-ws.org/Vol-2898/paper05.pdf.

[3] L. Fadieieva, S. Semerikov, Exploring the Interplay of Moodle Tools and Student Learning Outcomes: A Composite-Based Structural Equation Modelling Approach, in: E. Faure, Y. Tryus, T. Vartiainen, O. Danchenko, M. Bondarenko, C. Bazilo, G. Zaspa (Eds.), Information Technology for Education, Science, and Technics, volume 222 of *Lecture Notes on Data Engineering and Communications Technologies*, Springer Nature Switzerland, Cham, 2024, pp. 418–435. doi:10.1007/978-3-031-71804-5_28.

[4] K. Bondar, O. Shestopalova, V. A. Hamaniuk, V. Tursky, Ukraine higher education based on data-driven decision making (DDDM), in: S. Papadakis (Ed.), Joint Proceedings of the 10th Illia O. Teplytskyi Workshop on Computer Simulation in Education, and Workshop on Cloud-based Smart Technologies for Open Education (CoSinEi and CSTOE 2022) co-located with ACNS Conference on Cloud and Immersive Technologies in Education (CITEd 2022), Kyiv, Ukraine, December 22, 2022, volume 3358 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 53–72. URL: https://ceur-ws.org/Vol-3358/paper26.pdf.

[5] S. L. Kucher, R. M. Horbatiuk, M. M. Ozhha, N. M. Hryniaieva, Use of information and communication technologies in the organization of blended learning of future vocational education professionals, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 54–66. URL: https://ceur-ws.org/Vol-3679/paper39.pdf.

[6] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, V. N. Soloviev, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, V. R. Ruban, Mask and Emotion: Computer Vision in the Age of COVID-19, in: Digital Humanities Workshop, DHW 2021, Association for Computing Machinery, New York, NY, USA, 2022, p. 103–124. doi:10.1145/3526242.3526263.

[7] M. Velykodna, Psychoanalysis during the COVID-19 pandemic: Several reflections on countertransference, Psychodynamic Practice 27 (2021) 10–28. doi:10.1080/14753634.2020.1863251.

[8] O. Lushchak, M. Velykodna, S. Bolman, O. Strilbytska, V. Berezovskyi, K. B. Storey, Prevalence of stress, anxiety, and symptoms of post-traumatic stress disorder among Ukrainians after the first year of Russian invasion: a nationwide cross-sectional study, The Lancet Regional Health - Europe 36 (2024) 100773. doi:10.1016/j.lanepe.2023.100773.

[9] M. Velykodna, V. Deputatov, L. Kolisnyk, O. Shestopalova, O. Shylo, Psychological Service for Ukrainian School Students during the Russian Invasion: Experience of School Psychologists from Kryvyi Rih, International Journal of Child Health and Nutrition 12 (2023) 11–22. doi:10.6000/1929-4247.2023.12.01.2.

[10] R. P. Kukharchuk, T. A. Vakaliuk, O. V. Zaika, A. V. Riabko, M. G. Medvediev, Implementation of STEM learning technology in the process of calibrating an NTC thermistor and developing an electronic thermometer based on it, in: S. Papadakis (Ed.), Joint Proceedings of the 10th Illia O. Teplytskyi Workshop on Computer Simulation in Education, and Workshop on Cloud-based Smart Technologies for Open Education (CoSinEi and CSTOE 2022) co-located with ACNS Conference on Cloud and Immersive Technologies in Education (CITEd 2022), Kyiv, Ukraine, December 22, 2022, volume 3358 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 39–52. URL: https://ceur-ws.org/Vol-3358/paper25.pdf.

[11] M. M. Mintii, N. M. Sharmanova, A. O. Mankuta, O. S. Palchevska, S. O. Semerikov, Selection of pedagogical conditions for training STEM teachers to use augmented reality technologies in

their work, Journal of Physics: Conference Series 2611 (2023) 012022. doi:10.1088/1742-6596/2611/1/012022.
[12] M. M. Mintii, STEM education and personnel training: Systematic review, Journal of Physics: Conference Series 2611 (2023) 012025. doi:10.1088/1742-6596/2611/1/012025.
[13] T. H. Kolomoiets, D. A. Kassim, Using the Augmented Reality to Teach of Global Reading of Preschoolers with Autism Spectrum Disorders, in: A. E. Kiv, V. N. Soloviev (Eds.), Proceedings of the 1st International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, October 2, 2018, volume 2257 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018, pp. 237–246. URL: https://ceur-ws.org/Vol-2257/paper24.pdf.
[14] S. O. Semerikov, M. V. Foki, D. S. Shepiliev, M. M. Mintii, I. S. Mintii, O. H. Kuzminska, Methodology for teaching development of web-based augmented reality with integrated machine learning models, CEUR Workshop Proceedings 3771 (2024) 118–145. URL: https://ceur-ws.org/Vol-3820/paper249.pdf.
[15] O. M. Haranin, N. V. Moiseienko, Adaptive artificial intelligence in RPG-game on the Unity game engine, in: A. E. Kiv, S. O. Semerikov, V. N. Soloviev, A. M. Striuk (Eds.), Proceedings of the 1st Student Workshop on Computer Science & Software Engineering, Kryvyi Rih, Ukraine, November 30, 2018, volume 2292 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018, pp. 143–150. URL: http://ceur-ws.org/Vol-2292/paper16.pdf.
[16] S. Deterding, D. Dixon, R. Khaled, L. Nacke, From game design elements to gamefulness: defining “gamification”, in: Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments, MindTrek ’11, Association for Computing Machinery, New York, NY, USA, 2011, p. 9–15. doi:10.1145/2181037.2181040.
[17] J. Hamari, J. Koivisto, H. Sarsa, Does Gamification Work? – A Literature Review of Empirical Studies on Gamification, in: 2014 47th Hawaii International Conference on System Sciences, 2014, pp. 3025–3034. doi:10.1109/HICSS.2014.377.
[18] S. Subhash, E. A. Cudney, Gamified learning in higher education: A systematic review of the literature, Computers in Human Behavior 87 (2018) 192–206. doi:10.1016/j.chb.2018.05.028.
[19] D. Dicheva, C. Dichev, G. Agre, G. Angelova, Gamification in Education: A Systematic Mapping Study, Journal of Educational Technology & Society 18 (2015) 75–88. URL: http://www.jstor.org/stable/jeductechsoci.18.3.75.
[20] C. H.-H. Tsay, A. Kofinas, J. Luo, Enhancing student learning experience with technology-mediated gamification: An empirical study, Computers & Education 121 (2018) 1–17. doi:10.1016/j.compedu.2018.01.009.
[21] M. D. Hanus, J. Fox, Assessing the effects of gamification in the classroom: A longitudinal study on intrinsic motivation, social comparison, satisfaction, effort, and academic performance, Computers & Education 80 (2015) 152–161. doi:10.1016/j.compedu.2014.08.019.
[22] F. F.-H. Nah, Q. Zeng, V. R. Telaprolu, A. P. Ayyappa, B. Eschenbrenner, Gamification of Education: A Review of Literature, in: F. F.-H. Nah (Ed.), HCI in Business, volume 8527 of *Lecture Notes in Computer Science*, Springer International Publishing, Cham, 2014, pp. 401–409. doi:10.1007/978-3-319-07293-7_39.
[23] R. N. Landers, A. K. Landers, An Empirical Test of the Theory of Gamified Learning: The Effect of Leaderboards on Time-on-Task and Academic Performance, Simulation & Gaming 45 (2014) 769–785. doi:10.1177/1046878114563662.
[24] K. M. Kapp, The Gamification of Learning and Instruction: Game-based Methods and Strategies for Training and Education, John Wiley & Sons, 2012.
[25] A. Iosup, D. Epema, An experience report on using gamification in technical higher education, in: Proceedings of the 45th ACM Technical Symposium on Computer Science Education, SIGCSE ’14, Association for Computing Machinery, New York, NY, USA, 2014, p. 27–32. doi:10.1145/2538862.2538899.
[26] A. M. Toda, P. H. D. Valle, S. Isotani, The Dark Side of Gamification: An Overview of Negative Effects of Gamification in Education, in: A. I. Cristea, I. I. Bittencourt, F. Lima (Eds.), Higher Education for All. From Challenges to Novel Technology-Enhanced Solutions, volume 832 of

Communications in Computer and Information Science, Springer International Publishing, Cham, 2018, pp. 143–156. doi:10.1007/978-3-319-97934-2_9.

[27] E. D. Mekler, F. Brühlmann, A. N. Tuch, K. Opwis, Towards understanding the effects of individual gamification elements on intrinsic motivation and performance, Computers in Human Behavior 71 (2017) 525–534. doi:10.1016/j.chb.2015.08.048.

[28] C. E. Sylvester, Gamification in Education: Enhancing Student Engagement and Learning Outcomes, Research Output Journal of Arts and Management 3 (2024) 84–87. URL: https://www.researchgate.net/publication/383556065.

[29] M. Kurni, K. G. Srinivasa, IoT-Enabled Gamification for Education, in: The Internet of Educational Things: Enhancing Students' Engagement and Learning Performance, Springer Nature Switzerland, Cham, 2025, pp. 151–168. doi:10.1007/978-3-031-67387-0_10.

[30] M. Sailer, J. U. Hense, S. K. Mayr, H. Mandl, How gamification motivates: An experimental study of the effects of specific game design elements on psychological need satisfaction, Computers in Human Behavior 69 (2017) 371–380. doi:10.1016/j.chb.2016.12.033.

[31] O. Y. Burov, S. H. Lytvynova, S. O. Semerikov, Y. V. Yechkalo, ICT for disaster-resilient education and training, in: O. Y. Burov, S. H. Lytvynova, S. O. Semerikov, Y. V. Yechkalo (Eds.), Proceedings of the VII International Workshop on Professional Retraining and Life-Long Learning using ICT: Person-oriented Approach (3L-Person 2022), Virtual Event, Kryvyi Rih, Ukraine, October 25, 2022, volume 3482 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 1–25. URL: https://ceur-ws.org/Vol-3482/paper000.pdf.

[32] N. Rashevska, V. Tkachuk, Technological conditions of mobile learning at high school, Metallurgical and Mining Industry 3 (2015) 161–164.

[33] F. Handayani, A. Intes, G. Wibowo, D. Cahyono, B. Mardikawati, Quizzz! As A Tool For Innovative Educational Gamification In Higher Education, Journal Neosantara Hybrid Learning 2 (2024) 358–378. doi:10.55849/jnhl.v2i1.922.

[34] A. Saleem, B. Mirza, M. Ahmed, T. Fülöp, Students' and faculty continuous intention to use gamification in higher education: A structural analysis, Journal of Infrastructure, Policy and Development 8 (2024) 4609. doi:10.24294/jipd.v8i11.4609.

[35] L. Velázquez-García, M. Longar-Blanco, A. Cedillo-Hernández, E. Bustos-Farías, Gamification in the Classroom: Motivating Higher Education Students Using Digital Badges, International Journal of Learning and Teaching 10 (2023) 532–538. doi:10.18178/ijlt.10.4.532-538.

[36] S. Grey, N. A. Gordon, Increasing Engagement Through Explicit and Implicit Gamification in Higher Education, in: O. Bernardes, V. Amorim, A. C. Moreira (Eds.), Handbook of Research on the Influence and Effectiveness of Gamification in Education, IGI Global, Hershey, PA, 2022, pp. 662–681. doi:10.4018/978-1-6684-4287-6.ch032.

[37] L. Kalashnikova, I. Hrabovets, Motivation of modern Ukrainian teachers' professional activities: Generation archetypes, E3S Web of Conferences 166 (2020) 10002. doi:10.1051/e3sconf/202016610002.

Designing an immersive cloud-based educational environment for universities: a comprehensive approach

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Abstract

This paper presents a comprehensive approach to designing an immersive cloud-based educational environment (ICBEE) for universities. It defines the goals, structural components, functional modules, and actors of such an environment and provides a general metamodel reflecting its architecture. The paper suggests criteria for selection of immersive and cloud technologies, as well as guidelines for designing interactive learning content with augmented reality, virtual reality simulations and training applications. The proposed approach aims to create a methodological foundation for the development of ICBEEs as innovative ecosystems integrating advanced digital technologies and sound pedagogical practices to support active, personalized and practice-oriented learning.

Keywords

immersive learning, augmented reality, virtual reality, cloud technologies, educational environment, e-learning

1. Introduction

The ongoing digital transformation of higher education requires the development of innovative learning environments that leverage the potential of cutting-edge technologies to improve the quality and accessibility of educational services. Immersive learning approaches based on augmented reality (AR) and virtual reality (VR), coupled with the power and flexibility of cloud computing, open up new possibilities for designing interactive, engaging, and practice-oriented educational experiences [1].

An immersive cloud-based educational environment (ICBEE) can be defined as an integrated system that combines AR/VR tools, cloud services, learning management platforms, and various educational resources and activities to support learning, research, and management processes in a university setting [2, 3]. The design and implementation of such environments require a solid scientific and

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methodological foundation that takes into account the complex interplay of technological, pedagogical, and organizational factors.

The goal of this paper is to provide a comprehensive conceptual and methodological framework for designing ICBEEs at higher education institutions. The main objectives are:

- to define the goals, structural components, and main actors of ICBEE;
- to provide criteria for selection of AR/VR and cloud technologies for educational purposes;
- to suggest guidelines and principles for designing immersive learning content;
- to develop a general metamodel reflecting the architecture and key elements of ICBEE.

The rest of the paper is organized as follows. Section II provides a theoretical background on the concept and main components of ICBEE. Section III focuses on the principles and criteria for designing immersive learning content and selecting appropriate technologies. Section IV presents the results of the study in the form of a general metamodel of ICBEE and discusses its implications for the educational practice. Finally, Section V concludes the paper and outlines the directions for further research.

2. Theoretical background

2.1. The concept and goals of immersive cloud-based educational environment

The concept of immersive cloud-based educational environment (ICBEE) reflects the convergence of two major trends in modern education: the use of immersive technologies such as AR and VR to create more engaging and authentic learning experiences, and the adoption of cloud computing to enable flexible, scalable, and cost-effective delivery of educational services and resources [4].

The main goals of designing and implementing ICBEEs in higher education can be summarized as follows:

- to improve the quality of education by providing students with more interactive, personalized, and practice-oriented learning opportunities [5];
- to enhance the accessibility and flexibility of educational processes by leveraging the power of cloud platforms and services [6];
- to foster the development of students' and teachers' digital competencies required for effective learning and working in the modern technology-rich environment [7];
- to support innovative pedagogical approaches such as active learning, project-based learning, and remote collaboration [8];
- to enable data-driven decision-making and learning analytics based on the digital footprints of students' activities in the cloud-based environment [9].

Achieving these goals requires a holistic approach to the design of ICBEE that takes into account its complex structure and the interrelationships between its components.

2.2. Structural components of ICBEE

Based on the analysis of previous research [9], we can identify the following main structural components of an immersive cloud-based educational environment:

Spatial-semantic component, which includes the physical spaces of the university (classrooms, labs, collaboration zones) and their digital twins or virtual counterparts that can be accessed and interacted with using immersive technologies.

Technological component, which comprises the hardware and software infrastructure needed for the deployment and functioning of ICBEE, including:

- cloud platforms and services (IaaS, PaaS, SaaS) that host learning management systems (LMS), repositories, communication tools, and other applications [10];

- computing devices (servers, PCs, laptops) and specialized equipment for AR/VR experiences (headsets, controllers, trackers) [11];
- AR/VR development tools and frameworks (game engines, SDKs, libraries) used to create immersive learning content [12].

Content component, which encompasses the diverse types of digital learning resources and materials hosted in the cloud and accessible to students and teachers, such as e-books, video lectures, virtual labs, simulations, and assessments. This component also includes the data generated by the learning process itself (learning analytics, user activity logs, performance records) that can be used for personalization and improvement of educational services [13].

Communication component, which provides a set of tools and channels for synchronous and asynchronous learning interactions, collaboration, and experience sharing among the actors of the educational process. These may include video conferencing and webinar platforms, instant messaging and project management systems, social networks and forums.

Immersive component, which is specifically focused on AR/VR technologies and content that enable learners to interact with digital objects in a more natural and realistic way, creating a sense of presence and engagement. This component comprises:

- AR applications that overlay digital information onto the real world, e.g. by adding labels, 3D models, or instructions to physical objects or locations [14];
- VR simulations and virtual worlds that immerse the user in a fully digital environment, enabling them to practice skills, conduct experiments, and explore complex concepts in a safe and controlled way [15];
- 360-degree videos and images that provide an immersive view of real-world locations and phenomena, enhancing the learning experience and making it more memorable [16];
- haptic and motion tracking devices that enable more natural and intuitive interaction with virtual objects and environments [17].

These components form an integrated system in which the physical and digital spaces are blended, the learning process is mediated by a range of cloud-based tools and platforms, and the immersive technologies add an extra layer of interactivity and engagement. The design of ICBEE should ensure the seamless integration and interoperability of these components, as well as their alignment with the educational goals and pedagogical approaches.

2.3. Functional modules and services of ICBEE

The structural components of ICBEE described above are realized through a set of functional modules and services that support various aspects of the educational process. These include:

Learning management module (LMS), which serves as a central hub for organizing and delivering educational content, tracking student progress, and facilitating communication between teachers and students. Modern cloud-based LMS platforms such as Moodle, Canvas, or Blackboard provide a wide range of features and can be easily integrated with other tools and services [18].

Immersive learning content authoring and delivery module, which provides tools for creating, editing, and publishing AR/VR content such as 3D models, interactive simulations, and virtual tutorials. This module may include cloud-based platforms for 3D modeling and animation, AR/VR SDK and frameworks, as well as repositories for storing and sharing the created content.

Institutional repository module, which provides a centralized storage and access point for various types of digital learning resources and research outputs produced by the university staff and students. Cloud-based repository platforms such as DSpace or Eprints enable easy submission, description, and retrieval of materials, as well as their long-term preservation and accessibility.

Learning analytics and reporting module, which collects and processes data about students' learning activities, performance, and engagement in order to provide actionable insights for teachers, learners, and administrators. This module may include cloud-based tools for data mining, visualization, and dashboard creation, as well as predictive models for identifying students at risk and suggesting personalized interventions.

Communication and collaboration services, which enable synchronous and asynchronous interactions among the actors of the educational process, both within and beyond the classroom. These may include cloud-based tools for video conferencing, instant messaging, file sharing, and collaborative document editing, as well as social networking and project management platforms.

IT infrastructure management and security services, which ensure the reliable and secure operation of the cloud-based environment, including user authentication and authorization, data backup and recovery, performance monitoring, and cybersecurity measures.

The integration and interoperability of these modules and services is essential for creating a seamless and effective educational experience. The choice of specific tools and platforms should be based on their functionality, reliability, usability, and cost-effectiveness, as well as their compatibility with the existing IT infrastructure and the educational needs of the university.

3. Design of immersive learning content for ICBEE

3.1. Principles of designing immersive learning experiences

The effectiveness of immersive learning content in ICBEE largely depends on the proper application of key design principles that take into account the specificities of AR/VR technologies and their impact on the learning process. Based on the analysis of recent studies [2], we can identify the following main principles for designing immersive learning experiences:

1. **Interactivity and engagement**: the immersive content should enable learners to actively interact with digital objects and environments, manipulate them, and observe the consequences of their actions. This principle is essential for creating a sense of agency and involvement in the learning process.
2. **Realism and authenticity**: the virtual objects and environments should be designed to closely resemble their real-world counterparts in terms of appearance, behavior, and functionality. This principle is important for ensuring the transfer of knowledge and skills acquired in the virtual setting to real-life situations.
3. **Adaptability and personalization**: the immersive content should be flexible enough to accommodate different learning styles, preferences, and paces. It should provide learners with opportunities for customization, self-regulation, and choice, as well as adapt to their individual needs and performance.
4. **Multimodality and multisensory feedback**: the immersive learning experiences should engage multiple sensory channels (visual, auditory, haptic) and provide learners with rich and diverse feedback on their actions and progress. This principle is essential for enhancing the immersion, retention, and transfer of learning.
5. **Collaborative and social learning**: the immersive content should support various forms of collaboration and social interaction among learners, such as co-creation, peer feedback, and group problem-solving. This principle is important for fostering the development of soft skills, such as communication, teamwork, and leadership.
6. **Safety and ethics**: the immersive learning experiences should be designed with the physical and psychological safety of learners in mind. They should avoid any content or situations that may cause discomfort, distress, or harm, and adhere to the ethical standards and guidelines for the use of immersive technologies in education.

These principles should be applied in a balanced and context-specific way, taking into account the learning objectives, target audience, and available resources. The design process should involve a close collaboration between educators, subject matter experts, instructional designers, and AR/VR developers to ensure the alignment between the pedagogical goals and the technological solutions.

3.2. Guidelines for developing educational AR applications

Augmented reality (AR) is a powerful tool for enhancing the learning experience by overlaying digital information onto the real world and enabling learners to interact with it in a natural and intuitive way. Educational AR applications can be used for a wide range of purposes, such as visualizing complex concepts, providing contextual support, and gamifying the learning process [19]. To ensure the effectiveness and usability of AR applications in the context of ICBEE, the following guidelines should be followed:

- Use AR to provide contextually relevant information and guidance that enhances the understanding and retention of the learning material. For example, an AR application for a biology course may overlay labels, descriptions, and 3D models of organs onto a physical model of the human body.
- Leverage the unique affordances of AR, such as spatial anchoring, object recognition, and real-time tracking, to create immersive and interactive learning experiences. For example, an AR application for a history course may enable students to explore a virtual reconstruction of an ancient city by walking around a physical space and using their device as a "magic window".
- Use AR to scaffold and support the learning process by providing learners with timely feedback, hints, and prompts based on their actions and performance. For example, an AR application for a language learning course may use speech recognition to provide learners with real-time feedback on their pronunciation and suggest corrections.
- Design AR experiences that are accessible, inclusive, and user-friendly, taking into account the diverse needs and abilities of learners. This includes providing clear instructions, adjustable settings, and alternative modes of interaction (e.g., voice commands for learners with motor impairments).
- Integrate AR applications seamlessly into the overall learning flow and align them with the learning objectives, assessment strategies, and other digital tools used in the course. For example, an AR application for a chemistry lab may be linked to the corresponding sections of the e-textbook and the LMS gradebook.
- Ensure the technical stability, performance, and cross-platform compatibility of AR applications by using reliable development tools and frameworks (such as AR.js, ARCore, ARKit, or ARToolKit), optimizing the content for different devices and screen sizes, and providing clear instructions for installation and troubleshooting.
- Evaluate the effectiveness and usability of AR applications through user testing, learning analytics, and feedback from learners and educators. Use this data to iteratively improve the design and functionality of the applications and to inform future development efforts.

Some specific examples of educational AR applications that can be developed using these guidelines include:

- An AR-enhanced textbook for an engineering course that allows students to explore interactive 3D models of machines and mechanisms by pointing their device at specific pages or diagrams.
- A location-based AR game for an environmental science course that engages students in a simulated field study by placing virtual specimens, instruments, and data collection tasks in real-world settings.
- An AR-based language learning app that helps students practice vocabulary and grammar by overlaying translations, definitions, and examples onto real-world objects and scenes.

By following these guidelines and exploring the diverse possibilities of AR, educators and developers can create engaging and effective learning experiences that bridge the gap between the digital and physical worlds and support the development of 21st-century skills and competencies.

3.3. Approaches to designing VR simulations and training systems

Virtual reality (VR) simulations and training systems are among the most promising applications of immersive technologies in education, as they allow learners to practice skills, explore scenarios, and gain hands-on experience in a safe and controlled environment. In the context of ICBEE, VR simulations can be used for a wide range of purposes, such as medical training, scientific experiments, engineering design, and soft skills development [20]. To ensure the effectiveness and usability of VR simulations, the following approaches should be followed:

1. **Align the simulation design with the learning objectives and outcomes**: Start by clearly defining what skills, knowledge, and attitudes the learners should develop as a result of the VR experience, and use this as a basis for designing the content, interactions, and assessments.
2. **Create realistic and immersive environments that replicate the key aspects of the real-world setting**: Use high-quality 3D models, textures, and animations to create a visually compelling and believable environment that captures the relevant details and complexity of the simulated scenario.
3. **Provide learners with authentic and relevant tasks and challenges that require the application of the targeted skills and knowledge**: Design the simulation scenarios based on real-world problems, cases, or situations that learners are likely to encounter in their future professional or academic activities.
4. **Implement intuitive and natural interaction methods that mimic the real-world actions and behaviors**: Use VR controllers, haptic devices, or gesture recognition to enable learners to manipulate objects, navigate the environment, and perform tasks in a way that feels natural and realistic.
5. **Provide learners with adaptive feedback, guidance, and support based on their individual performance and needs**: Use intelligent tutoring systems, real-time analytics, and machine learning algorithms to track learners' actions, assess their progress, and provide personalized recommendations and scaffolding.
6. **Allow for collaborative and social learning experiences that foster teamwork, communication, and problem-solving skills**: Design multi-user VR simulations that enable learners to work together, share resources, and coordinate their actions towards a common goal, while providing tools for communication and awareness.
7. **Ensure the safety, comfort, and well-being of learners by following the best practices and guidelines for VR design and use**: This includes providing clear instructions and warnings, allowing for frequent breaks and adjustable settings, and avoiding any content or interactions that may cause motion sickness, eye strain, or psychological distress.
8. **Integrate VR simulations into the broader learning ecosystem by linking them with other digital tools, platforms, and resources**: For example, a VR medical simulation may be accompanied by an e-textbook, a discussion forum, and a performance dashboard that are all accessible through the LMS.
9. **Evaluate the effectiveness and impact of VR simulations through rigorous research and continuous improvement**: Use a combination of quantitative and qualitative methods, such as learning analytics, user surveys, and expert reviews, to assess the learning outcomes, user experience, and return on investment of VR simulations, and use this data to refine and optimize their design.

Some examples of VR simulations and training systems that can be developed using these approaches include:

- A VR laboratory for a chemistry course that allows students to conduct virtual experiments, manipulate 3D models of molecules, and observe chemical reactions in a safe and reproducible way.

- A VR clinical simulation for a nursing program that enables students to practice patient assessment, diagnosis, and treatment skills in a realistic hospital environment, with virtual patients that respond to their actions and decisions [21].
- A VR design studio for an architecture course that provides students with tools for creating, exploring, and presenting 3D models of buildings and landscapes, while collaborating with peers and experts from around the world.

By leveraging the immersive and interactive capabilities of VR, educators can create powerful learning experiences that bridge the gap between theory and practice, foster deep understanding and long-term retention, and prepare learners for the challenges and opportunities of the real world.

4. General metamodel of ICBEE

Based on the analysis of the structural components, functional modules, and design principles of immersive cloud-based educational environments presented in the previous sections, we propose a general metamodel of ICBEE that captures its key elements and their relationships (figure 1). The metamodel consists of four main layers:

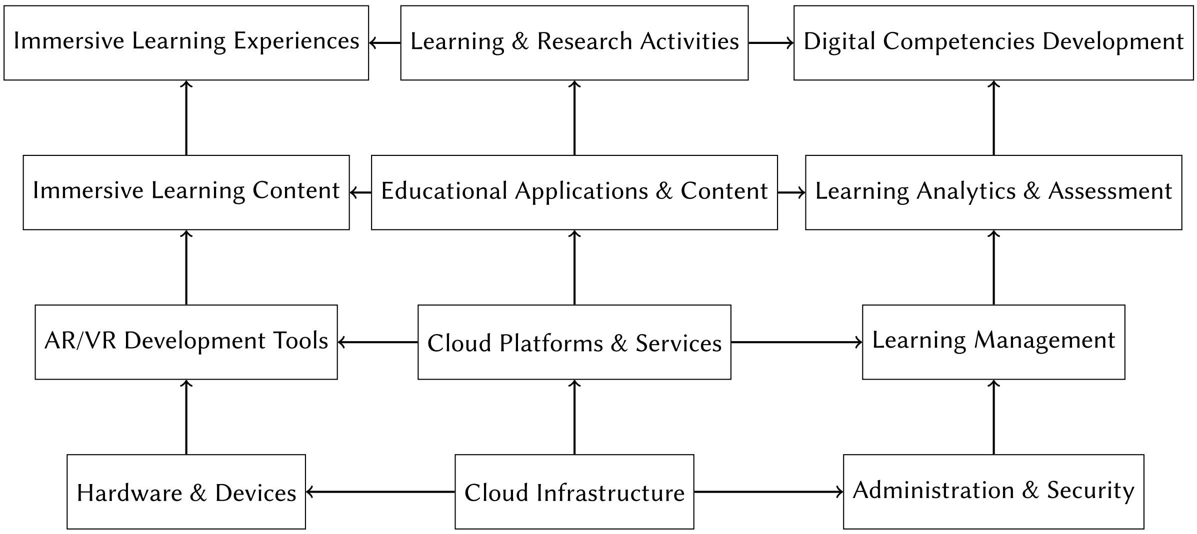

Figure 1: General metamodel of ICBEE.

1. The **Infrastructure** layer, which includes the physical and virtual computing resources, such as servers, storage, and networks, that support the operation of the cloud-based environment. This layer also encompasses the administration and security services that ensure the reliable, efficient, and safe functioning of the infrastructure.
2. The **Platforms and Services** layer, which includes the software components and tools that enable the development, deployment, and management of educational applications and content in the cloud. This layer consists of two sub-layers: (a) the general-purpose cloud platforms and services, such as learning management systems, collaboration tools, and data analytics engines; and (b) the specialized AR/VR development tools and frameworks, such as game engines, 3D modeling software, and device-specific SDKs.
3. The **Educational Content and Applications** layer, which includes the digital resources and software tools that are used directly by learners and educators in the learning process. This layer consists of two sub-layers: (a) the general educational content and applications, such as e-textbooks, video lectures, simulations, and assessments; and (b) the immersive learning content and applications, such as AR/VR simulations, 360-degree videos, and haptic interfaces.

4. The **Learning and Research Activities** layer, which includes the various forms of educational activities and experiences that are supported by the ICBEE, such as lectures, labs, projects, and research. This layer consists of two sub-layers: (a) the general learning and research activities, such as problem-based learning, collaborative learning, and scientific inquiry; and (b) the immersive learning experiences that leverage the unique affordances of AR/VR technologies, such as embodied learning, situational learning, and experiential learning.

The arrows in the metamodel represent the relationships and dependencies between the different layers and components. For example, the cloud infrastructure provides the necessary computing resources and services for the development and deployment of educational applications, while the AR/VR development tools enable the creation of immersive learning content that is used in the learning activities. The learning activities, in turn, generate data and feedback that can be analyzed using learning analytics tools to improve the quality and effectiveness of the educational content and applications.

The metamodel also highlights the cross-cutting aspects of ICBEE, such as the development of learners' digital competencies, which is supported by all layers of the environment, from the use of innovative hardware and software tools to the participation in authentic and meaningful learning activities. Another important cross-cutting aspect is the integration and interoperability of the different components and services, which is essential for creating a seamless and coherent learning experience.

The proposed metamodel provides a high-level conceptual framework for understanding the key components and relationships of immersive cloud-based educational environments. It can serve as a basis for the design, development, and evaluation of specific ICBEE implementations, as well as for the identification of research challenges and opportunities in this field. The metamodel can also be used as a communication tool for facilitating the dialogue and collaboration between the different stakeholders involved in the creation and use of ICBEE, such as educators, learners, researchers, IT professionals, and policymakers.

5. Conclusion

This paper presented a comprehensive approach to designing immersive cloud-based educational environments (ICBEEs) for higher education institutions. The proposed approach is based on a thorough analysis of the key components, functional modules, design principles, and development guidelines for ICBEEs, as well as on a review of relevant research and practice in the field.

The main contributions of the paper include: (a) a conceptual framework for understanding the goals, structure, and functions of ICBEEs; (b) a set of criteria and recommendations for selecting and integrating immersive and cloud technologies in educational settings; (c) a collection of design principles and guidelines for creating effective and engaging immersive learning content and experiences; and (d) a general metamodel that captures the key elements and relationships of ICBEEs and provides a high-level roadmap for their design and implementation.

The proposed approach and metamodel can serve as a foundation for further research and development in the field of immersive and cloud-based learning technologies. Some potential directions for future work include:

- Developing and evaluating specific ICBEE implementations for different educational contexts, domains, and levels, and studying their impact on learning outcomes, motivation, and satisfaction of learners and educators.
- Investigating the pedagogical, technological, and organizational factors that influence the adoption, use, and sustainability of ICBEEs in higher education institutions, and identifying the best practices and lessons learned from successful cases.
- Exploring the potential of emerging technologies, such as virtual and augmented reality, artificial intelligence, and learning analytics, to enhance the functionality and effectiveness of ICBEEs, and addressing the technical, ethical, and societal challenges associated with their use.

- Conducting comparative studies of different ICBEE designs and implementations, and developing benchmarks and standards for evaluating their quality, efficiency, and impact on learning and teaching.
- Examining the implications of ICBEEs for the roles, competencies, and professional development of educators, and designing training programs and support services that enable them to effectively integrate immersive and cloud-based technologies into their teaching practice.

Immersive cloud-based educational environments represent a promising and transformative approach to learning and teaching in higher education, one that leverages the power of advanced technologies to create engaging, personalized, and authentic learning experiences. The design and implementation of effective ICBEEs require a holistic and interdisciplinary approach that takes into account the complex interplay of technological, pedagogical, and organizational factors, and that is grounded in research-based principles and guidelines. The proposed metamodel and recommendations provide a starting point for this endeavor, but much work remains to be done to fully realize the potential of ICBEEs and to address the challenges and opportunities they present for the future of higher education.

References

[1] Ö. Yılmaz, Personalised learning and artificial intelligence in science education: current state and future perspectives, Educational Technology Quarterly 2024 (2024) 255–274. doi:10.55056/etq.744.

[2] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, Immersive cloud-based educational environment of the university: Design principles, CEUR Workshop Proceedings 3771 (2024) 126–135. URL: https://ceur-ws.org/Vol-3771/paper27.pdf.

[3] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, Development of digital competencies in immersive cloud-based educational environment, CEUR Workshop Proceedings 3781 (2024) 203–208. URL: https://ceur-ws.org/Vol-3781/paper27.pdf.

[4] S. Aoki, Y. Ohkawa, T. Hayashida, Y. Takiguchi, Cloud-based Rendering System for Presentation of Immersive Media on Various Types of Devices, in: Proceedings of the 2024 ACM International Conference on Interactive Media Experiences, IMX '24, Association for Computing Machinery, New York, NY, USA, 2024, p. 328–333. doi:10.1145/3639701.3663633.

[5] O. Aleksandrova, I. Hroznyi, N. Vinnikova, N. Chuvasova, Control of the quality assurance system at the modern Ukrainian university, Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2019 (2019) 153–162. doi:10.29202/nvngu/20192/18.

[6] P. Nechypurenko, T. Selivanova, M. Chernova, Using the Cloud-Oriented Virtual Chemical Laboratory VLab in Teaching the Solution of Experimental Problems in Chemistry of 9th Grade Students, in: V. Ermolayev, F. Mallet, V. Yakovyna, V. S. Kharchenko, V. Kobets, A. Kornilowicz, H. Kravtsov, M. S. Nikitchenko, S. Semerikov, A. Spivakovsky (Eds.), Proceedings of the 15th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kherson, Ukraine, June 12-15, 2019, volume 2393 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 968–983. URL: https://ceur-ws.org/Vol-2393/paper_329.pdf.

[7] O. Kuzminska, M. Mazorchuk, N. Morze, M. Prokopchuk, H. Danylchuk, Integrating digital competencies of researchers into Ph.D. curricula: a case study on open science education, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 195–208. URL: https://ceur-ws.org/Vol-3679/paper36.pdf.

[8] S. L. Malchenko, M. S. Tsarynnyk, V. S. Poliarenko, N. A. Berezovska-Savchuk, S. Liu, Mobile technologies providing educational activity during classes, Journal of Physics: Conference Series 1946 (2021) 012010. doi:10.1088/1742-6596/1946/1/012010.

[9] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, V. N. Soloviev, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, D. S. Shepiliev, Immersive E-Learning Resources: Design Methods, in: Digital Humanities Workshop, DHW 2021, Association for Computing Machinery, New York, NY, USA, 2022, p. 37–47. URL: https://doi.org/10.1145/3526242.3526264.

[10] K. Vlasenko, O. Chumak, D. Bobyliev, I. Lovianova, I. Sitak, Development of an Online-Course Syllabus "Operations Research Oriented to Cloud Computing in the CoCalc System", in: A. Bollin, H. C. Mayr, A. Spivakovsky, M. V. Tkachuk, V. Yakovyna, A. Yerokhin, G. Zholtkevych (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume I: Main Conference, Kharkiv, Ukraine, October 06-10, 2020, volume 2740 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 278–291. URL: https://ceur-ws.org/Vol-2740/20200278.pdf.

[11] S. O. Semerikov, M. M. Mintii, I. S. Mintii, Review of the course "Development of Virtual and Augmented Reality Software" for STEM teachers: implementation results and improvement potentials, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 159–177. URL: https://ceur-ws.org/Vol-2898/paper09.pdf.

[12] S. O. Semerikov, M. V. Foki, D. S. Shepiliev, M. M. Mintii, I. S. Mintii, O. H. Kuzminska, Methodology for teaching development of web-based augmented reality with integrated machine learning models, CEUR Workshop Proceedings 3771 (2024) 118–145. URL: https://ceur-ws.org/Vol-3820/paper249.pdf.

[13] S. S. Iyer, L. Gernal, R. Subramanian, A. Mehrotra, Impact of digital disruption influencing business continuity in UAE higher education, Educational Technology Quarterly 2023 (2023) 18–57. doi:10.55056/etq.29.

[14] T. H. Kolomoiets, D. A. Kassim, Using the Augmented Reality to Teach of Global Reading of Preschoolers with Autism Spectrum Disorders, in: A. E. Kiv, V. N. Soloviev (Eds.), Proceedings of the 1st International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, October 2, 2018, volume 2257 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018, pp. 237–246. URL: https://ceur-ws.org/Vol-2257/paper24.pdf.

[15] Y. Fan, Integrating online and offline teaching to promote creativity for STEM learners, Educational Technology Quarterly 2024 (2024) 241–254. doi:10.55056/etq.723.

[16] S. H. Lytvynova, S. O. Semerikov, A. M. Striuk, M. I. Striuk, L. S. Kolgatina, V. Y. Velychko, I. S. Mintii, O. O. Kalinichenko, S. M. Tukalo, AREdu 2021 - Immersive technology today, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 1–40. URL: https://ceur-ws.org/Vol-2898/paper00.pdf.

[17] M. M. Mintii, STEM education and personnel training: Systematic review, Journal of Physics: Conference Series 2611 (2023) 012025. doi:10.1088/1742-6596/2611/1/012025.

[18] A. R. Chasubuta, P. M. Ndibalema, P. Loisulie, Technological literacy in using Learning Management System among students in higher education institutions Tanzania: the case of two selected universities, Educational Technology Quarterly 2024 (2024) 76–96. doi:10.55056/etq.695.

[19] E. Polat, Gamification implementation for educational purposes: a scoping review (2013-2018), Educational Technology Quarterly 2023 (2023) 367–400. doi:10.55056/etq.589.

[20] Z. Ying, Experience of intelligent speech robot in music online classroom based on deep learning and virtual reality, Entertainment Computing 52 (2025) 100795. doi:10.1016/j.entcom.2024.100795.

[21] S. Y. Liaw, J. Z. Tan, S. Lim, W. Zhou, J. Yap, R. Ratan, S. L. Ooi, S. J. Wong, B. Seah, W. L. Chua, Artificial intelligence in virtual reality simulation for interprofessional communication training: Mixed method study, Nurse Education Today 122 (2023) 105718. doi:10.1016/j.nedt.2023.105718.

Enhancing mathematics education with GeoGebra and augmented reality

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Abstract

This article explores the potential of integrating GeoGebra software with augmented reality (AR) technology to enhance mathematics education. Recent studies have shown promising results in using GeoGebra AR to promote spatial skills, conceptual understanding, and engagement in fields like geometry, algebra, and calculus. Examples of GeoGebra AR applications in educational settings are provided, spanning both secondary and higher education. Recommendations for further research and implementation are discussed. The integration of GeoGebra AR into mathematics curricula, coupled with appropriate teacher training and support, has the potential to revolutionize how students encounter and engage with mathematical concepts.

Keywords

augmented reality, GeoGebra 3D, mathematics education

1. Introduction

Mathematics education constantly evolves to incorporate new technologies that can enhance teaching and learning [1]. GeoGebra, a powerful dynamic mathematics software, has gained widespread adoption in recent years [2]. GeoGebra allows for interactive exploration of mathematical concepts through dynamic visualizations. More recently, GeoGebra has ventured into the realm of augmented reality (AR) with its GeoGebra AR applications. AR overlays virtual information onto the real world, creating immersive experiences that merge the physical and digital [3, 4, 5]. The combination of GeoGebra and AR presents exciting opportunities for engaging students with mathematical ideas in new ways.

The purpose of this article is to examine the current state of research on GeoGebra AR in mathematics education and to provide examples of its applications across various mathematical domains and educational levels. We also offer examples and recommendations for successful integration into mathematics curricula.

2. GeoGebra AR in secondary mathematics education

Several studies have investigated the impact of GeoGebra AR on mathematics learning at the secondary level. Del Cerro Velázquez and Méndez [6] found that integrating GeoGebra AR into a secondary geometry curriculum improved students' spatial intelligence and academic performance compared to traditional instruction. In a quasi-experimental study, Guntur and Setyaningrum [7] reported that secondary students who used an AR module with GeoGebra had significantly higher spatial and problem-solving skills than those in a control group.

GeoGebra AR has been applied to various mathematical topics in secondary education:

- In **geometry**, GeoGebra AR allows students to visualize and manipulate 3D shapes, explore cross-sections, and discover geometric properties [8, 9]. Lainufar et al. [10] described a project-based

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geometry unit where secondary students used GeoGebra AR, reporting high levels of acceptance and engagement.

- For **algebra**, graphing functions and surfaces in AR provides an intuitive way to understand their behavior and characteristics [11].
- GeoGebra AR can support the learning of **trigonometric functions** by allowing students to explore graphs and transformations in an immersive 3D environment [12].

Mailizar and Johar [13] used the Technology Acceptance Model (TAM) to examine factors affecting secondary students' intention to use GeoGebra AR in a project-based geometry unit. They found perceived usefulness to be the strongest predictor of behavioral intention, highlighting the importance of demonstrating the practical value of AR tools.

These studies provide evidence for the effectiveness of GeoGebra AR in promoting spatial abilities, conceptual understanding, and engagement in secondary mathematics. However, more research is needed to understand its long-term effects on achievement and attitudes.

3. GeoGebra AR in higher education and STEAM

At the tertiary level, GeoGebra AR has been explored in various mathematics courses and in interdisciplinary STEAM (Science, Technology, Engineering, Arts, and Mathematics) contexts [14].

In a calculus course, Caridade [15] used GeoGebra AR to visualize 3D graphs and solids of revolution, reporting increased student engagement and understanding. Similarly, Cheong et al. [16] found GeoGebra AR to be an effective tool for teaching multivariable calculus, particularly in enhancing visualization of 3D surfaces.

GeoGebra AR has also been applied in engineering mathematics. Iparraguirre-Villanueva et al. [17] integrated GeoGebra AR into a spatial geometry course for engineering students, finding improved performance and positive attitudes compared to a control group.

In STEAM education, GeoGebra AR allows for the integration of mathematical modeling with arts, culture, and history. El Bedewy et al. [18, 19, 20] describe STEAM practices where participants model historical architecture using GeoGebra AR and 3D printing, connecting mathematical concepts to cultural heritage. These interdisciplinary approaches can make mathematics more engaging and meaningful for students.

Cahyono and Lavicza [21] explored how STEAM projects involving GeoGebra AR and 3D printing can be designed for cross-country math trails. Pre-service teachers created AR models of local landmarks and linked them to school mathematics topics, allowing users in different countries to engage with the math trail.

These examples demonstrate the versatility of GeoGebra AR in higher education, from traditional mathematics courses to innovative STEAM projects. More research is needed on the affordances and challenges of implementing GeoGebra AR in these diverse contexts.

4. Augmented reality and mathematical thinking

Augmented reality technology has the potential to support and enhance key aspects of mathematical thinking. Nam et al. [22] argue that GeoGebra AR can serve as a tool to connect abstract mathematical knowledge to real-world situations, using the example of learning about parallel lines and planes in space. By manipulating AR models, students can test hypotheses, refine their ideas, and construct new knowledge.

Bagossi et al. [23] developed an analytical tool called the Timeline to investigate the relationship between student-teacher-artifact interactions and meaning-making when using GeoGebra AR. Their analysis revealed how different phases of AR-supported activities contributed to students' mathematical development.

In a study on second-order covariation, Bagossi and Swidan [24] compared students' reasoning in GeoGebra and AR environments. While both environments supported covariation, the AR group showed fuller emergence of the concept after physical experimentation, highlighting the role of embodied interactions.

Walkington et al. [25] examined the new kinds of embodied interactions that arise in an AR-based version of GeoGebra, using the Microsoft HoloLens 2. They found that the immersive 3D environment afforded novel interactions related to perspective, scale, and depth, with implications for the design of future AR math tools.

These studies provide initial insights into how AR technology, and GeoGebra AR specifically, can shape students' mathematical thinking and reasoning. More research is needed to unpack the cognitive processes involved and to design AR-based tasks that optimize learning.

5. Case study: stereometry teaching

5.1. Tasks on combinations of polyhedron and solids of revolution

Consider the way it is possible to inscribe a sphere into the right rectangular pyramid via the use of 3D Geometry. In order to construct the base of the pyramid, it is necessary to use the Right Polygon tool, by pointing two points on the 3D canvas – adjacent vertexes of the base, and indicating that the right polygon has 4 vertexes. Then one should construct the diagonals of the square (the Segment tool) and define the center (Intersection point). Then through the center of the square, which is also the center of the circle inscribed in the square, one draws a straight line perpendicular to the plane of the square. On this straight line, one chooses an arbitrary point (Point on the object) and constructs a polyhedron (Pyramid). The perpendicular to the plane of the square straight line is the geometric location of points, equidistant from the sides of the base of the right pyramid.

To determine the position of the center inscribed sphere in the pyramid, one constructs a geometric location of points that are equidistant from the edges of the dihedral angle at the base of the pyramid. Since there is no construction of the bisector plane in the GeoGebra tools, it is necessary to construct a linear angle of the dihedral angle at the base and then bisector of the very angle. The plane passing through the vertex of the pyramid perpendicular to the edge of the base is built (Plane through the point perpendicular to the straight line; Intersection point). Instead of a plane, it is possible to draw a straight line from the vertex of the pyramid perpendicular to the edge of the base (straight, perpendicular to straight). Next, one should find the intersection point of the constructed plane / perpendicular with the edge of the base (Intersection point of the straight line and the plane / Intersection point of two straight lines). Then one builds the bisector of the obtained linear angle.

The point of its intersection with the perpendicular to the base of the pyramid, drawn from the top of the pyramid, will determine the center of the inscribed sphere (Point of intersection). Finally, one constructs the inscribed sphere (Sphere outside the center and radius), specifying in sequence the center of the sphere and the point of intersection of the diagonals of the square [26].

For better understanding and mastering of the algorithm the construction of the sphere inscribed around the pyramid the students setting of the canvas are adjusted to be able to show the step-by-step procedure of the construction.

With AR, the students can understand the basic concepts of 3D geometrical shapes, their relationships and ways to construct the 3D shapes and the objects in 3D space. Importantly, AR can provide a dynamic visualization of 3D structures of geometrical shapes. This feature helps the students to understand a comprehensive background of 3D geometrical shapes and improve the abilities of geometrical structures. Moreover, the hand gesture based interactions furnish an intuitive and convenient way for the students to directly control and interact with geometrical shapes in 3D space.

GeoGebra Augmented Reality application allows you to transfer the constructed figure into the space of the room (figure 1. Having built a figure, we press the "AR" button. Next, you need to use the camera to select the environment in which we plan to move the object. For example, on the table. By tapping on the screen, the figure will be transferred to the real world [27] where it can be explored. The phone camera will serve our eyes. Immersing the phone in a virtual figure we will see it from the inside, we can bypass it, also the application allows you to resize, color [28].

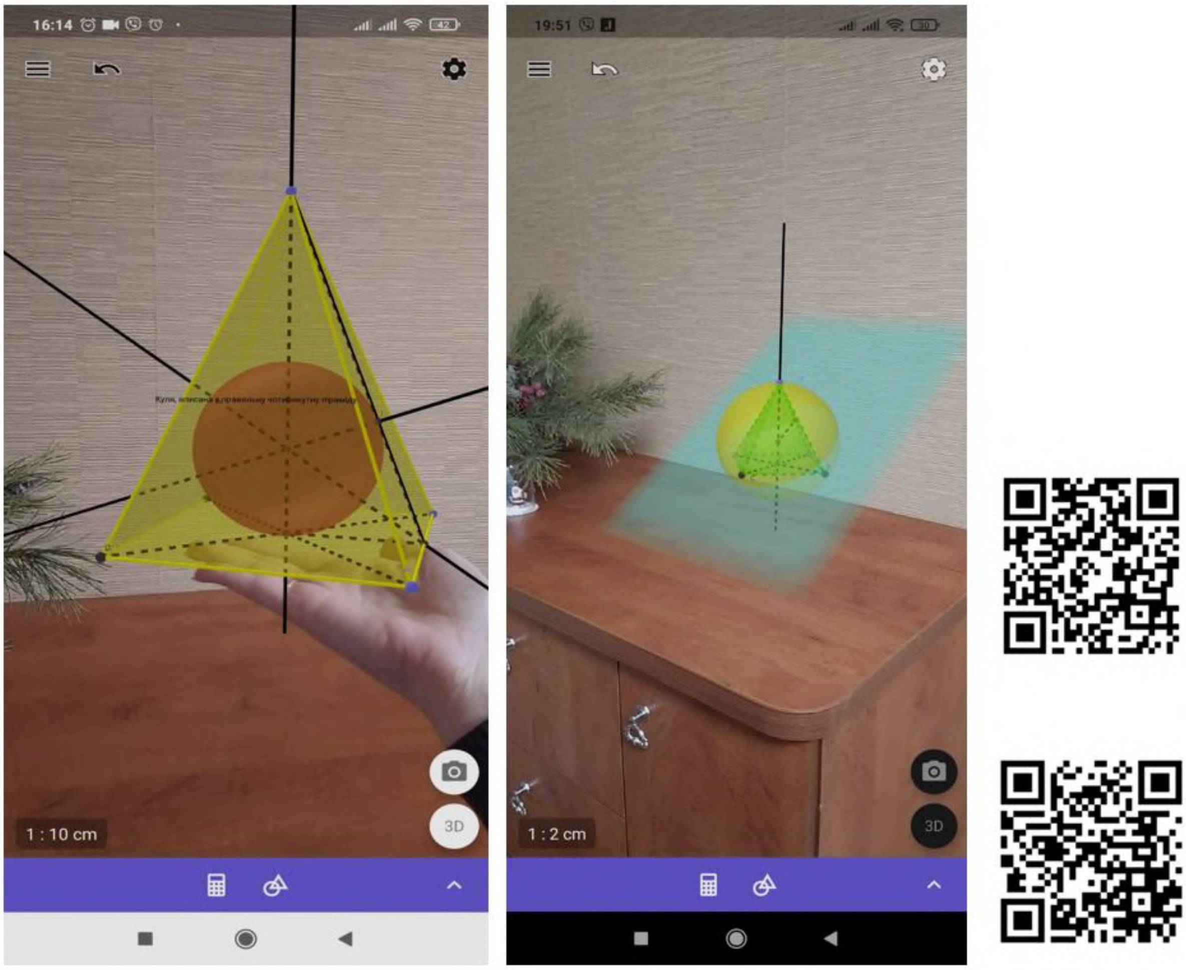

Figure 1: GeoGebra AR demos.

With the experiences of interacting with the 3D shapes using their own hand gestures, the students can improve their own awareness of the relationships of the 3D shapes and easily remember or retain the knowledge about the 3D shapes.

5.2. Stereometric problems of applied content

Geometry is an abstract science, often taught without proper implementation of its applied orientation. This leads to the fact that a significant part of students do not feel the need to study this subject, because they do not see the possibility of using the acquired geometric knowledge, in particular in stereometry, in the future. And so there is a need to connect stereometric problems with life. We propose to consider two problems of applied direction, for the solution of which we consider it expedient to involve the GeoGebra 3D application. We offered these tasks to students of the State University of Economics and Technologies.

Problem 1. What percentage of wood goes to waste when made of wooden logs, 5 m long and 20 cm and 15 cm in diameter, beams with a rectangular cross-section of the maximum cross-sectional area?

Problem 2. Calculate the volume of the largest beam with a base in the shape of a rectangle, which can be carved from a log of cylindrical shape. The length of the log is 5 m and the thickness is 20 cm. What percentage of wood will go to waste?

Using these tasks, we conducted research on the basis of two parallel groups majoring in “Finance and Credit”. 18 students of the experimental group (EG) and 17 students of the control group (CG) took part in the study. In the experimental group, the task was to solve problems based on a dynamic figure, the control group solved the same problems, but with the help of static.

The proposed questionnaire consisted of several questions that students answered while solving problems.

1. What figures will we work with? Positive answer: CG – 6 students (35%), EG – 7 students (39%).
2. How are the figures relative to each other? Positive answer: CG – 7 students (41%), EG – 7 students (39%).
3. What shape should be the cross section of the beam to maximize its size? The volume of the beam will be the largest if the cross section of the beam is square. It is not necessary to compose a function and study it to the extreme, it is enough to use the formula to calculate the area of a quadrilateral inscribed in a circle. Positive answer: CG – 4 students (24%), EG – 3 students (17%). In the second stage, the CG group was shown a figure for the problem on paper, the EG group was shown a figure in GeoGebra (figure 2) and considered in dynamics.
4. After that, the groups were asked the last question about the cross-section again, the statistics of positive answers improved: CG – 6 students (35%), EG – 9 students (50%).
5. What is meant by waste from the manufacture of logs? The positive answer that this is the difference between the volume of the truncated cone and the volume of the parallelepiped was given by: CG – 9 students (53%), EG – 12 students 67%.

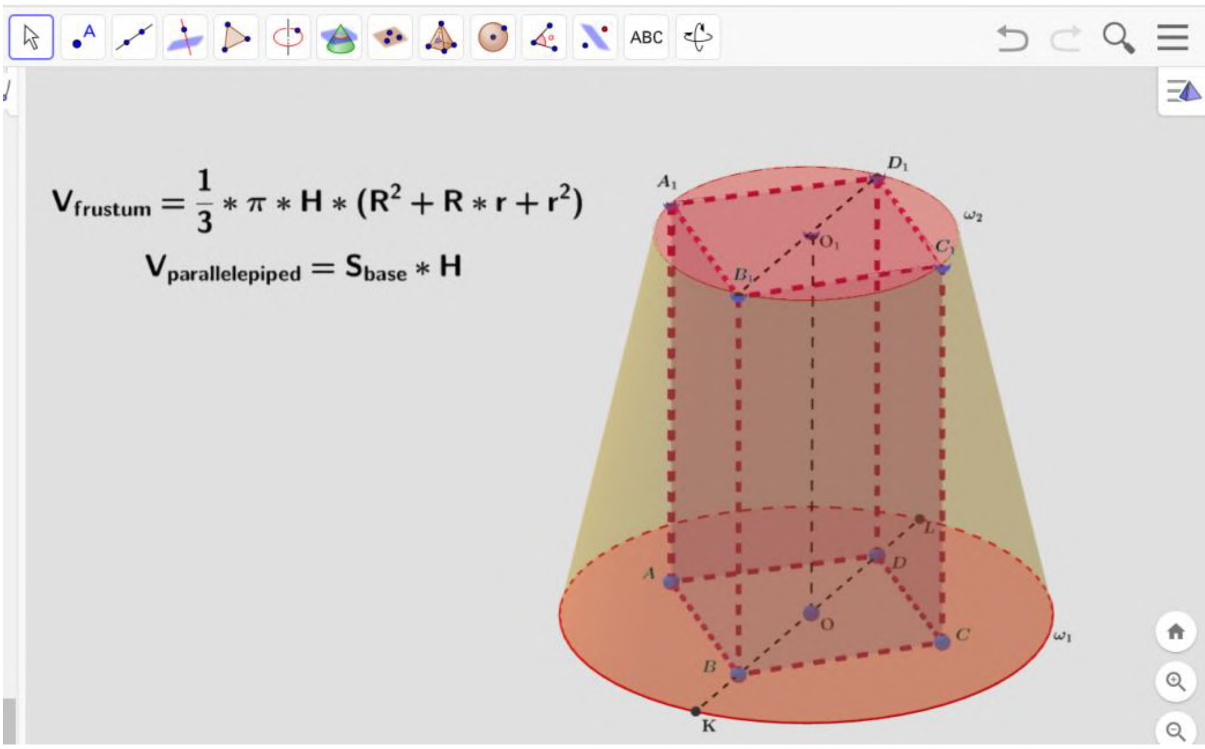

Figure 2: A parallelepiped inscribed in a truncated cone.

The dynamic image in GeoGebra helped the EG group to improve the statistics of responses, after the demonstration of the figure on paper this effect could not be achieved. The results of the survey showed that the highest efficiency is achieved when demonstrating dynamic models.

Optimization tasks using Geogebra were proposed by us in the textbook [27]. We supplemented the sets of tasks using Geogebra with visual aids for specialized teaching of mathematics, realization of interdisciplinary connections of the beginnings of mathematical analysis and stereometry. In this case, you can use the expressions to calculate the volume of the body to track the change in this value and find the optimal size of the beam. It is also advisable to use the "Function Inspector" tool in GeoGebra to find the extreme values of the function and visualize the abstractions.

It is convenient to write the formulas on the canvas at once, and then open them step by step during the discussion. To make such a blank in the application GeoGebra 3D, you must first build a truncated cone (by crossing the cone plane), then through the center of a smaller circle and a point on it build a line. Draw a perpendicular line to the obtained line, choosing the center of a smaller circle as a point. Mark the points of intersection of the lines with the circle and through the obtained 4 points build a square (using the Polygon tool), connecting the points in series. From the vertices of the square we lower the perpendiculars to the lower base of the cone (larger circle) and mark the points of intersection of the perpendiculars with the plane of the base of the cone, through the obtained 4 points we build a square, connecting the points in series. Using the Prism tool, build a prism by selecting a polygon of the base (square) and the vertex at one of the points of the smaller circle.

During the in-depth study of mathematics at the Kryvyi Rih Pokrovsky Lyceum, we offered students the problem of stereometry for optimization according to the textbook by Skanavi [29]. After calculating the optimal dimensions of the prism / pyramid, the polygon scan was drawn and glued. Models in dynamics created by means of system of dynamic mathematics were offered for demonstrations. Here are examples of mathematical problems that students had to reformulate as problems of applied content.

1. (15.194) What are the dimensions of the base radius and the height of the open cylindrical tank, so that at a given volume V for its manufacture was spent the least amount of sheet metal?
2. (15.195) The side face of a regular quadrangular pyramid has a constant given area and is inclined to the plane of the base at an angle α. At what value of α is the volume of the pyramid the largest?
3. (15.196) In a regular quadrangular pyramid with the edge of the base a and the height H, a regular quadrangular prism is inscribed so that its lower base is located at the base of the pyramid, and the vertices of the upper base are placed on the side edges. Find the edge of the base and the height of the prism that has the largest side surface.
4. (15.197) The side edge of a right triangular pyramid has a constant given length and forms an angle α with the plane of the base. At what value of α will the volume of the pyramid be the largest?
5. (15.198) In a regular triangular pyramid, the side face has a constant given constant area and forms an angle α with the plane of the base. At what value of α is the distance from the center of the base of the pyramid to its side face the largest?
6. (15.199) A pyramid is inscribed in a cone with a given constant volume, which is based on an isosceles triangle with an angle at the vertex equal to α. At what value of α is the volume of the pyramid the largest?
7. (15.200) The generating cone has a constant length and forms an angle α with the height of the cone. A regular hexagonal prism with equal edges is inscribed in the cone (the base of the prism is located in the plane of the base of the cone). At what value of α is the side surface of the prism the largest?

Solving problems of applied content will provide an opportunity to motivate, intensify the educational and cognitive activities of students and promote the practical application of acquired knowledge.

5.3. Project work in GeoGebra 3D

One of the effective means of developing students' cognitive activity is the project method. After all, the project method includes a set of research, search, problem, creative approaches, promotes the creative development of students, prepares them to solve problem situations in everyday life. Therefore, it is advisable to offer students to perform mini-projects while studying the section of stereometry.

The task of the project will be to build a playground in the GeoGebra 3D application, using the maximum number of studied geometric shapes: prisms, pyramids, spheres, cones, cylinders, etc. (figure 3). Performance appraisal is a mandatory element of the organization of project work. The effectiveness of the project lies in the ratio of planned expectations with the final results. Created designs can be designed in the yard with an augmented reality application.

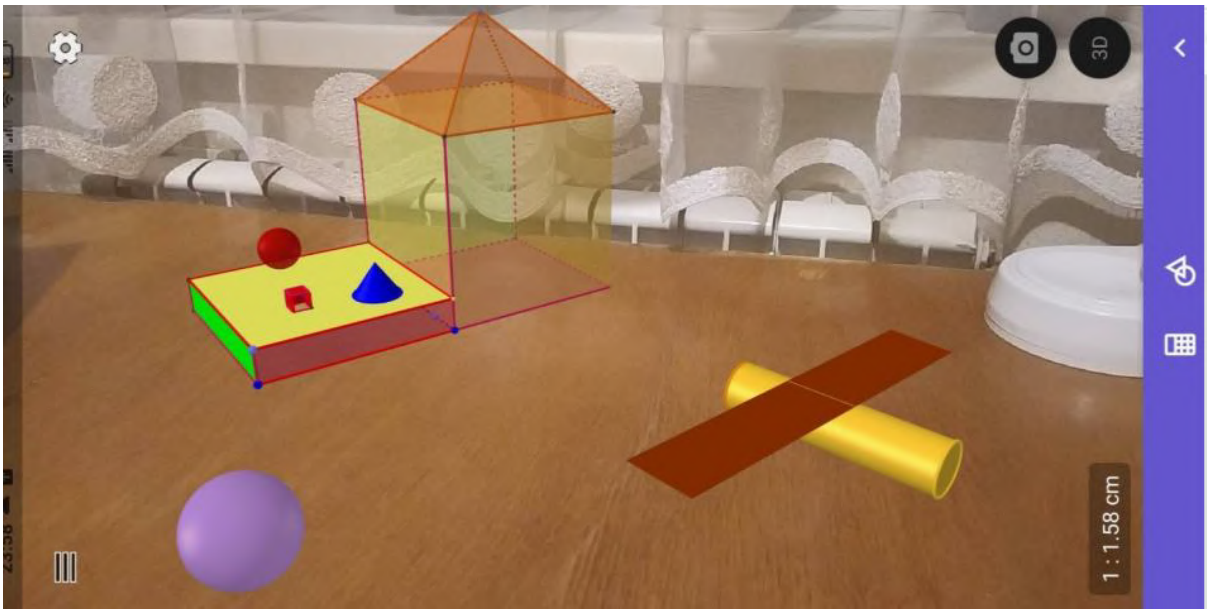

Figure 3: Sample implementation of the project "Playground".

There are three stages of self-regulated, namely the Planning Phase, at this stage students set steps for learning, namely (1) Analyzing learning tasks, (2) Determining learning objectives, and (3) Planning learning strategies. In the analyzing stage, students implement a plan that is constantly monitored to ensure it leads to learning goals. In the determining stage, students determine how well the learning strategy is chosen and how to achieve these learning goals [30].

Students were also asked to develop a project "Artist's Room", in which students will model a room from improvised means, and before that it is advisable to offer to make a layout in GeoGebra. In this way, students will already know where to start, what sizes of objects to take, what colors will impress, what shapes are needed to create a room, they will learn to break an object into simple geometric bodies and shapes.

Project work interests students in the subject, increases mental activity and creative thinking, helps to mobilize knowledge in practice and quickly adapt to unusual situations. During the construction of a playground or an artist's room, students use innovative abilities, invention, STEM competencies are formed, such as critical thinking, creativity, organizational skills, teamwork, emotional intelligence, ability to interact effectively, cognitive flexibility.

6. Integrating GeoGebra AR into mathematics curricula

To effectively incorporate GeoGebra AR into mathematics curricula, educators should consider the following guidelines [31]:

1. Choose AR activities that align with learning objectives and promote active engagement.
2. Provide students with clear instructions and scaffold their exploration in the AR environment.
3. Encourage collaborative learning and discussion to solidify conceptual understanding.
4. Assess learning outcomes and gather feedback to refine implementation.

Professional development is crucial for teachers to learn best practices for using GeoGebra AR [32]. Teacher education programs should expose pre-service teachers to the capabilities of GeoGebra AR and how to integrate it purposefully into their future classrooms.

Successful integration also requires attention to technological infrastructure and equity. Schools need access to AR-capable devices and reliable internet, and teachers need ongoing technical support. Ensuring equal access to AR learning experiences for all students is an important consideration.

7. Conclusion and future work

GeoGebra AR represents a promising frontier in mathematics education, offering dynamic, interactive experiences that bridge the gap between abstract concepts and the real world. Research has begun to demonstrate its potential to enhance spatial reasoning, conceptual understanding, and engagement in mathematics at both the secondary and tertiary levels. Thoughtful integration of GeoGebra AR into mathematics curricula, coupled with teacher training and ongoing support, can enrich students' learning experiences.

As GeoGebra AR continues to evolve, several areas merit further research and development:

- More work is needed to design and evaluate professional development models that prepare teachers to effectively integrate GeoGebra AR into their practice.
- The potential of GeoGebra AR to bridge mathematics with other STEAM fields deserves further exploration, building on initial work in architecture, arts, and culture [18, 19, 20].
- More research is needed to understand how the embodied interactions afforded by GeoGebra AR shape students' mathematical thinking and problem solving [25].
- The role of GeoGebra AR in supporting mathematics learning across different instructional modes, including remote and hybrid settings, should be investigated.

References

[1] K. Vlasenko, S. Volkov, I. Sitak, I. Lovianova, D. Bobyliev, Usability analysis of on-line educational courses on the platform "Higher school mathematics teacher", E3S Web of Conferences 166 (2020) 10012. doi:10.1051/e3sconf/202016610012.

[2] M. Hohenwarter, J. Hohenwarter, Y. Kreis, Z. Lavicza, Teaching and Learning Calculus with Free Dynamic Mathematics Software GeoGebra, in: ICME 11 – 11th International Congress on Mathematical Education, Nuevo Leon, Monterrey, 2008.

[3] A. Teichrew, R. Erb, How augmented reality enhances typical classroom experiments: Examples from mechanics, electricity and optics, Physics Education 55 (2020). doi:10.1088/1361-6552/abb5b9.

[4] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, Immersive cloud-based educational environment of the university: Design principles, CEUR Workshop Proceedings 3771 (2024) 126–135. URL: https://ceur-ws.org/Vol-3771/paper27.pdf.

[5] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, Development of digital competencies in immersive cloud-based educational environment, CEUR Workshop Proceedings 3781 (2024) 203–208. URL: https://ceur-ws.org/Vol-3781/paper27.pdf.

[6] F. Del Cerro Velázquez, G. M. Méndez, Application in augmented reality for learning mathematical functions: A study for the development of spatial intelligence in secondary education students, Mathematics 9 (2021) 1–19. doi:10.3390/math9040369.

[7] M. I. S. Guntur, W. Setyaningrum, The Effectiveness of Augmented Reality in Learning Vector to Improve Students' Spatial and Problem-Solving Skills, International Journal of Interactive Mobile Technologies 15 (2021) 159–173. doi:10.3991/ijim.v15i05.19037.

[8] T. H. Kramarenko, O. S. Pylypenko, V. I. Zaselskiy, Prospects of using the augmented reality application in STEM-based Mathematics teaching, in: A. E. Kiv, M. P. Shyshkina (Eds.), Proceedings of the 2nd International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine,

March 22, 2019, volume 2547 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 130–144. URL: https://ceur-ws.org/Vol-2547/paper10.pdf.

[9] M. Shabanova, O. Bezumova, E. Zatsepina, S. Malysheva, S. Kotova, R. Ovchinnikova, Learning stereometry in a secondary school within GeoGebra's Augmented Reality app, Journal of Physics: Conference Series 1691 (2020) 012115. doi:10.1088/1742-6596/1691/1/012115.

[10] Lainufar, M. Mailizar, R. Johar, Exploring the potential use of GeoGebra augmented reality in a project-based learning environment: The case of geometry, Journal of Physics: Conference Series 1882 (2021) 012045. doi:10.1088/1742-6596/1882/1/012045.

[11] I. H. Batubara, S. Saragih, E. Simamora, E. E. Napitupulu, N. Nuraini, D. N. Sari, A. Anim, I. P. Sari, E. Rahmadani, E. Syafitri, Improving Student Mathematics Communication Ability through Problem Based Learning Assisted by Augmented Reality Based on Culture, AIP Conference Proceedings 2659 (2022). doi:10.1063/5.0113258.

[12] V. Ferdiánová, J. Poruba, Augmented reality in lecture on constructional geometry, in: 19th Conference on Applied Mathematics, APLIMAT 2020 Proceedings, Slovak University of Technology in Bratislava, 2020, pp. 408–417.

[13] Mailizar, R. Johar, Examining students' intention to use augmented reality in a project-based geometry learning environment, International Journal of Instruction 14 (2021) 773–790. doi:10.29333/iji.2021.14243a.

[14] T. Tkachenko, O. Yeremenko, A. Kozyr, V. Mishchanchuk, W. Liming, Integration Aspect of Training Teachers of Art Disciplines in Pedagogical Universities, Journal of Higher Education Theory and Practice 22 (2022) 138–147. doi:10.33423/jhetp.v22i6.5236.

[15] C. M. R. Caridade, GeoGebra Augmented Reality: Ideas for Teaching and Learning Math, in: F. Yilmaz, A. Queiruga-Dios, M. J. Santos Sánchez, D. Rasteiro, V. Gayoso Martínez, J. Martín Vaquero (Eds.), Mathematical Methods for Engineering Applications, volume 384 of *Springer Proceedings in Mathematics & Statistics*, Springer International Publishing, Cham, 2022, pp. 235–244. doi:10.1007/978-3-030-96401-6_22.

[16] K. H. Cheong, C. E. Chu, W. K. Ng, D. J. Yeo, Implementing GeoGebra 3D Calculator With Augmented Reality in Multivariable Calculus Education, IEEE Access 12 (2024) 85455–85464. doi:10.1109/ACCESS.2024.3394531.

[17] O. Iparraguirre-Villanueva, C. Paulino-Moreno, H. Chero-Valdivieso, K. Espinola-Linares, M. Cabanillas-Carbonell, Integration of GeoGebra Calculator 3D with Augmented Reality in Mathematics Education for an Immersive Learning Experience, International Journal of Engineering Pedagogy 14 (2024) 92–107. doi:10.3991/ijep.v14i3.47323.

[18] S. El Bedewy, K. Choi, Z. Lavicza, K. Fenyvesi, T. Houghton, STEAM Practices to Explore Ancient Architectures Using Augmented Reality and 3D Printing with GeoGebra, Open Education Studies 3 (2021) 176–187. doi:10.1515/edu-2020-0150.

[19] S. El Bedewy, Z. Lavicza, B. Haas, D. Lieban, A STEAM Practice Approach to Integrate Architecture, Culture and History to Facilitate Mathematical Problem-Solving, Education Sciences 12 (2022) 9. doi:10.3390/educsci12010009.

[20] S. El Bedewy, Z. Lavicza, I. Lyublinskaya, Steam practices connecting mathematics, arts, architecture, culture and history in a non-formal learning environment of a museum, Journal of Mathematics and the Arts 18 (2024) 101 – 134. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85187476020&doi=10.1080%2f17513472.2024.2321563&partnerID=40&md5=96624b28c6517e95f91cd254502aea78. doi:10.1080/17513472.2024.2321563.

[21] A. N. Cahyono, Z. Lavicza, Designing Landmark-Based STEAM Projects for Cross-Country Math Trail Activities with Augmented Reality and 3D Printing Technologies, International Journal for Technology in Mathematics Education 30 (2023) 241–246. doi:10.1564/tme_v30.4.6.

[22] P. S. Nam, L. H. Thai, Z. Lavicza, A. Schmid, T. Houghton, Augmented Reality as a Tool to Support the Connection Between Reality and Mathematical Knowledge: A Case for Teaching Parallel Relations of Planes in Space, International Journal for Technology in Mathematics Education 31 (2024) 135–142. doi:10.1564/tme_v31.3.04.

[23] S. Bagossi, O. Swidan, F. Arzarello, Timeline tool for analyzing the relationship between students-

teachers-artifacts interactions and meaning-making, Journal on Mathematics Education 13 (2022) 357–382. doi:10.22342/jme.v13i2.pp357-382.

[24] S. Bagossi, O. Swidan, Learning Second-order Covariation with GeoGebra and Augmented Reality, International Journal for Technology in Mathematics Education 30 (2023) 213–218. doi:10.1564/tme_v30.4.2.

[25] C. Walkington, M. J. Nathan, J. Hunnicutt, J. Washington, M. Zhou, New kinds of embodied interactions that arise in augmented reality dynamic geometry software, Journal of Mathematical Behavior 75 (2024) 101175. doi:10.1016/j.jmathb.2024.101175.

[26] T. H. Kramarenko, O. S. Pylypenko, I. O. Muzyka, Application of GeoGebra in Stereometry teaching, CEUR Workshop Proceedings 2643 (2020) 705–718.

[27] T. H. Kramarenko, O. S. Pylypenko, GeoGebra AR Demo: The sphere is inscribed in a pyramid, Video, 2021. URL: https://youtu.be/oohbLc19Llo.

[28] T. H. Kramarenko, O. S. Pylypenko, GeoGebra AR Demo: A sphere described around a right quadrangular pyramid, Video, 2021. URL: https://youtu.be/JSkdu1lgWlg.

[29] M. I. Skanavi (Ed.), Collection of problems in mathematics for applicants to universities, Minsk, 1990.

[30] M. Tomaschko, S. A. Kocadere, M. Hohenwarter, Opportunities for Participation, Productivity, and Personalization Through GeoGebra Mathematics Apps, in: A. A. Khan, S. Umair (Eds.), Handbook of Research on Mobile Devices and Smart Gadgets in K-12 Education, IGI Global, Hershey, 2018, pp. 45–56. doi:10.4018/978-1-5225-2706-0.ch004.

[31] B. Haas, Y. Kreis, Z. Lavicza, Integrated STEAM Approach in Outdoor Trails with Elementary School Pre-service Teachers, Educational Technology and Society 24 (2021) 205–219.

[32] N. V. Osypova, V. I. Tatochenko, Improving the learning environment for future mathematics teachers with the use application of the dynamic mathematics system GeoGebra AR, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 178–196. URL: https://ceur-ws.org/Vol-2898/paper10.pdf.

The utility of free software in teaching of mathematics, physics and computer science for pre-service teachers

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Abstract

The increasing digitalization of education has led to a need for pre-service teachers in mathematics, physics and computer science to develop competencies in utilizing information and communication technologies (ICT) in their teaching practice. Free and open source software presents a valuable opportunity for educators to access powerful tools without the financial and legal barriers associated with proprietary software. This article examines the theoretical and methodological foundations for integrating free software into the professional training of pre-service teachers of mathematics, physics and computer science, based on the findings of a doctoral thesis by Velychko [1]. The study proposes a system for applying free software in teacher education, encompassing conceptual, content and technological components. Experimental results demonstrate the effectiveness of the proposed system in enhancing the ICT competencies of pre-service teachers. The article highlights the benefits and challenges of utilizing free software in education and provides recommendations for its implementation in teacher training programs.

Keywords

free software, teacher training, the concept of implementation

1. Introduction

The rapid advancement of technology in the 21st century has had a profound impact on all sectors of society, including education [2]. Teachers are expected to possess not only subject knowledge but also the skills to effectively integrate ICT into their teaching practice [3, 4]. However, the cost and licensing restrictions of proprietary software can present significant barriers for educational institutions, particularly in developing countries [5]. Free and open source software (FOSS) offers a solution by providing access to high-quality tools without the associated financial and legal constraints [6, 7].

The use of FOSS in education has been a topic of research for several decades [8, 9]. Studies have shown that FOSS can be effectively utilized in various educational contexts, including engineering [10], computer science [11] and science education [12]. However, the integration of FOSS in teacher education programs, particularly for pre-service teachers of mathematics, physics and computer science, remains an underexplored area.

This article aims to address this gap by examining the theoretical and methodological foundations for applying FOSS in the professional training of pre-service teachers of mathematics, physics and computer science. The article is based on the findings of a doctoral thesis by Velychko [1], which proposed a system for integrating FOSS into teacher education programs in Ukraine. The article presents an overview of the proposed system, its components and the experimental results of its implementation. The benefits and challenges of utilizing FOSS in teacher education are discussed, along with recommendations for its effective integration into training programs.

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2. Theoretical foundations

2.1. The concept of free software

Free software is defined by the Free Software Foundation as software that respects the freedom and community of its users [13]. This freedom is enshrined in four essential rights: the freedom to run the program for any purpose, the freedom to study how the program works and adapt it to one's needs, the freedom to redistribute copies, and the freedom to improve the program and release those improvements to the public [14].

The philosophy of free software aligns closely with the principles of academic freedom and the open sharing of knowledge [15]. Universities have played a key role in the development of free software, with many groundbreaking projects originating from research labs and student communities [1].

2.2. ICT competencies for teachers

The integration of ICT into education has become a global priority, as evidenced by the UNESCO ICT Competency Framework for Teachers [16]. This framework outlines the knowledge and skills that teachers need to effectively utilize ICT in their professional practice, including [17]:

- Understanding the role of ICT in education
- Curriculum and assessment
- Pedagogy
- ICT
- Organization and administration
- Teacher professional learning

For pre-service teachers of mathematics, physics and computer science, developing ICT competencies is particularly crucial, as these subjects often involve the use of specialized software tools and computational methods [18, 19]. However, research has shown that many teacher education programs do not adequately prepare pre-service teachers to integrate ICT into their teaching practice [20].

2.3. Benefits of free software in education

The use of free software in education offers several significant benefits, including:

- *Cost savings* – free software eliminates the need for expensive licensing fees, making it more accessible for educational institutions with limited budgets [21].
- *Flexibility* – the open source nature of free software allows educators to customize and adapt tools to meet their specific needs [22].
- *Skill development* – working with free software can help students develop valuable technical skills, such as programming and problem-solving [23].
- *Collaboration* – free software projects often have active communities of users and developers, providing opportunities for students and educators to collaborate and learn from each other [24].

Despite these benefits, the adoption of free software in education faces several challenges, including lack of awareness, technical support and training for educators [25].

3. A system for applying free software in teacher education

Velychko [1] proposed a system for integrating free software into the professional training of pre-service teachers of mathematics, physics and computer science. The system consists of three main components (figure 1).

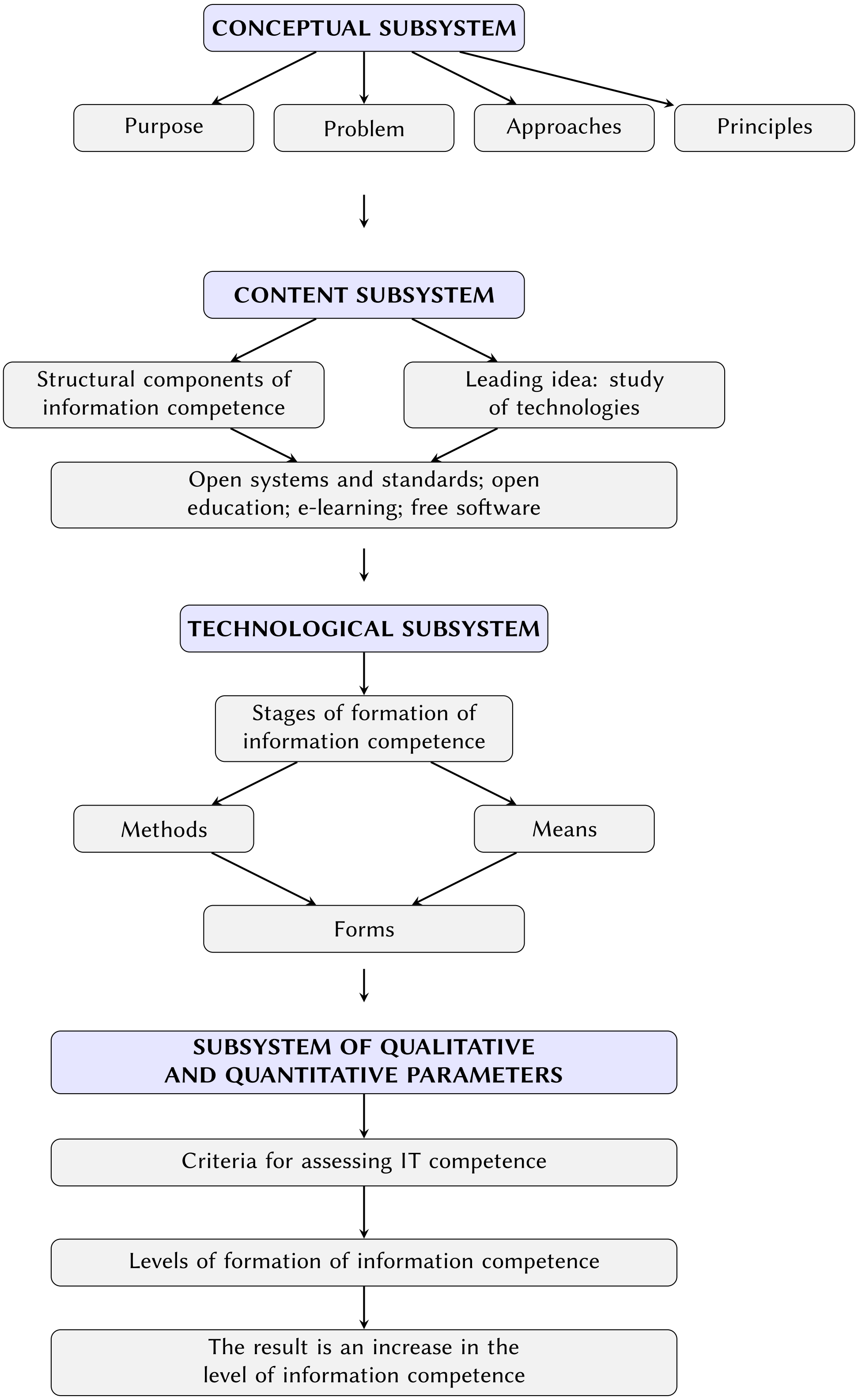

Figure 1: System for integrating free software into the professional training of pre-service teachers of mathematics, physics and computer science.

3.1. Conceptual component

The conceptual component outlines the goals, objectives, approaches and principles of the system. The main goal is to enhance the ICT competencies of pre-service teachers through the use of free software. The objectives include providing access to powerful tools, developing technical skills and promoting collaboration. The system is grounded in competency-based, innovation-oriented and synergetic approaches to learning.

3.2. Content component

The content component defines the structure and content of ICT competencies for pre-service teachers, as well as the key concepts and ideas related to free software in education. The competencies encompass knowledge, skills and attitudes in areas such as:

- Information and data literacy
- Communication and collaboration
- Digital content creation
- Safety
- Problem-solving

The content component also emphasizes the importance of open educational resources, e-learning and the role of free software in enabling open education practices.

3.3. Technological component

The technological component focuses on the practical implementation of the system, including the stages of ICT competency development, teaching methods, tools and forms of learning. The stages of development are:

1. Motivational-purposeful
2. Exploratory
3. Orientational-planning
4. Control-evaluative
5. Regulatory-corrective

The teaching methods include problem-based learning, project-based learning and collaborative learning. The tools used are primarily free software applications for mathematics, physics and computer science, such as GeoGebra, Python and LaTeX. The forms of learning include lectures, laboratory work, independent study and project-based activities.

4. Experimental results

Velychko [1] conducted an experimental study to evaluate the effectiveness of the proposed system in enhancing the ICT competencies of pre-service teachers. The study involved 240 students from pedagogical universities in Ukraine, divided into control and experimental groups.

The results showed that the experimental group, which was taught using the free software-based system, had significantly higher levels of ICT competency compared to the control group. In particular, the experimental group demonstrated better skills in using free software tools for problem-solving, digital content creation and collaboration.

The study also found that the use of free software in teacher education had a positive impact on students' motivation and engagement in learning. Students reported feeling more empowered and confident in their ability to use technology in their future teaching practice.

5. Discussion and recommendations

The findings of Velychko [1] demonstrate the potential of free software as a valuable tool for enhancing the ICT competencies of pre-service teachers. By providing access to powerful, flexible and collaborative tools, free software can help bridge the digital divide and prepare future teachers to effectively integrate technology into their teaching practice.

However, the successful integration of free software in teacher education requires more than just access to tools. It also requires a supportive institutional environment, adequate technical infrastructure and ongoing professional development opportunities for educators [26].

Based on the findings of this study, the following recommendations are proposed for integrating free software into teacher education programs:

- Raise awareness about the benefits of free software among educators, administrators and policymakers.
- Provide training and support for educators to effectively use free software tools in their teaching practice.
- Encourage collaboration and sharing of resources among educators, both within and across institutions.
- Integrate free software into the curriculum, not just as a separate subject but as a tool for enhancing learning across disciplines.
- Foster partnerships with free software communities and industry to provide real-world learning opportunities for students.

6. Conclusion

The integration of free software into the professional training of pre-service teachers of mathematics, physics and computer science presents a promising approach for enhancing their ICT competencies and preparing them for the challenges of 21st century education. By leveraging the power of free software, teacher education programs can provide access to high-quality tools, foster collaboration and skill development, and promote open education practices.

However, realizing the full potential of free software in teacher education requires a concerted effort from educators, institutions and policymakers. It requires awareness-raising, capacity-building and the creation of supportive environments that encourage experimentation and innovation.

As the world becomes increasingly digital, it is imperative that we equip future teachers with the skills and tools they need to navigate this landscape effectively. Free software offers a path forward that is both accessible and empowering, and it is up to us as educators to seize this opportunity and make it a reality.

References

[1] V. Y. Velychko, Theoretical and methodical principles of the use of free software in the training of pre-services teachers of mathematics, physics and computer science, The thesis for the Degree of Doctor of Pedagogical Sciences degree in the specialty 13.00.04 – Theory and Methodic of Professional Training and 13.00.10 – Information and Communication Technologies in Education, State Higher Educational Establishment „Donbas State Pedagogical University", Sloviansk, 2019. URL: https://ddpu.edu.ua/images/stories/news/specrada/191219/Velichko/velychko01.pdf.

[2] J.-Z. Zhang, H.-M. Xiong, X.-C. Peng, Free software SSP for teaching mathematics, in: Symbolic Computation and Education, World Scientific Publishing Co., 2007, pp. 115–135. doi:10.1142/9789812776006_0007.

[3] V. Y. Velychko, E. H. Fedorenko, D. A. Kassim, Conceptual Bases of Use of Free Software in the Professional Training of Pre-Service Teacher of Mathematics, Physics and Computer Science, in:

A. E. Kiv, V. N. Soloviev (Eds.), Proceedings of the 1st International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, October 2, 2018, volume 2257 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2018, pp. 93–102. URL: https://ceur-ws.org/Vol-2257/paper11.pdf.

[4] V. Tkachuk, S. Semerikov, Y. V. Yechkalo, S. Khotskina, V. N. Soloviev, Selection of Mobile ICT for Learning Informatics of Future Professionals in Engineering Pedagogy, in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 1058–1068. URL: https://ceur-ws.org/Vol-2732/20201058.pdf.

[5] E. Laugasson, J. S. Quaicoe, E. Jeladze, T. Jesmin, Bridging Digital Divide in Schools in Developing Countries: Perceptions of Teachers of Free Software Opportunities, in: P. Zaphiris, A. Ioannou (Eds.), Learning and Collaboration Technologies, volume 9753 of *Lecture Notes in Computer Science*, Springer International Publishing, Cham, 2016, pp. 695–706. doi:10.1007/978-3-319-39483-1_63.

[6] J. W. Stockwell Jr., Free software in education: A case study of CWP/SU: Seismic Un*x, Leading Edge (Tulsa, OK) 16 (1997) 1045. doi:10.1190/1.1437723.

[7] F. J. Garcia, I. Alvarez, Left case - a free software component-based case tool for software engineering practice support, in: 33rd Annual Frontiers in Education, 2003. FIE 2003., volume 3, 2003, pp. S2C_7–S2C_12. doi:10.1109/FIE.2003.1265945.

[8] M. Arufe Martínez, Free software on the Internet: Teaching applications in toxicology; [Programas informáticos de libre distribución en Internet: Aplicaciones educativas en toxicología], Revista de Toxicologia 18 (2001) 5–7.

[9] G. D. Moss, Comparing awareness and use of content-free software in comprehensive schools, Computers and Education 18 (1992) 283–291. doi:10.1016/0360-1315(92)90100-J.

[10] I. Munch, W. Wagner, Free software development in civil engineering and an application for the design of industrial sheds; [Freie softwareentwicklung im bauingenieurwesen am beispiel der bemessung von industriehallen], Bauingenieur 86 (2011) 400–408.

[11] D. Megías, J. Serra, R. MacAu, An international master programme in free software in the european higher education space, in: OSS 2005 - Proceedings of the 1st International Conference on Open Source Systems, 2005, pp. 349–352.

[12] R. C. Fortenberry, A. R. McDonald, T. D. Shepherd, M. Kennedy, C. D. Sherrill, PSI4Education: Computational chemistry labs using free software, ACS Symposium Series 1193 (2015) 85–98. doi:10.1021/bk-2015-1193.ch007.

[13] R. Stallman, Viewpoint: Why “open source” misses the point of free software, Communications of the ACM 52 (2009) 31–33. doi:10.1145/1516046.1516058.

[14] G. Perens, J. Chyu, K. McHenry, T. Yoshida, J. P. Finn, Three-Dimensional Congenital Heart Models Created With Free Software and a Desktop Printer: Assessment of Accuracy, Technical Aspects, and Clinical Use, World Journal for Pediatric and Congenital Heart Surgery 11 (2020) 797–801. doi:10.1177/2150135120952072.

[15] G. Goetz, A song of teaching with free software in the Anthropocene, Educational Philosophy and Theory 54 (2022) 545–556. doi:10.1080/00131857.2021.1962706.

[16] L. Amestica Rivas, W. Contreras-Higuera, A. King-Domínguez, F. Quezada Quezada, E. Cornejo-Saavedra, Use of free software in engineering courses; [Aprendizaje a través del uso de portfolio digital, innovando en la asignatura de formulación económica de proyectos], Espacios 37 (2016) 1.

[17] R. M. Bitegeko, G. Lawrent, J. Cosmas, Applying the UNESCO ICT competency framework to evaluate digital competencies among undergraduate students in teacher education in Tanzania, Educational Technology Quarterly 2024 (2024) 298–318. doi:10.55056/etq.769.

[18] K. V. Vlasenko, O. O. Chumak, I. V. Lovianova, V. V. Achkan, I. V. Sitak, Personal e-Learning Environment of the Maths teacher’ online course as a means of improving ICT competency of a Mathematics teacher, Journal of Physics: Conference Series 2288 (2022) 012038. doi:10.1088/1742-6596/2288/1/012038.

[19] V. Pichot, C. Corbier, F. Chouchou, J.-C. Barthélémy, F. Roche, CVRanalysis: a free software for analyzing cardiac, vascular and respiratory interactions, Frontiers in Physiology 14 (2023). doi:10.3389/fphys.2023.1224440.

[20] E. Laugasson, M. Mõttus, Free Software User Interfaces: Usability and Aesthetics, in: P. Zaphiris, A. Ioannou (Eds.), Learning and Collaboration Technologies, volume 9192 of *Lecture Notes in Computer Science*, Springer International Publishing, Cham, 2015, pp. 676–686. doi:10.1007/978-3-319-20609-7_63.

[21] A. J. McMullen, Electronic reserves on a budget a case study of a homegrown system built with open source and free software solutions, Journal of Interlibrary Loan, Document Delivery and Electronic Reserve 17 (2007) 137–150. doi:10.1300/J474v17n01_13.

[22] A. Cacabelos, M. E. Arce, J. L. Míguez, C. Míguez, Integration of the free software genopt for a thermal engineering course, Computer Applications in Engineering Education 24 (2016) 356–364. doi:10.1002/cae.21713.

[23] A. Fedosov, M. Markushevich, T. Gubina, Free Software at School and the Educational Process: Current State, Systematization of Typical Problems, in: R. Silhavy, P. Silhavy, Z. Prokopova (Eds.), Software Engineering Application in Informatics, volume 232 of *Lecture Notes in Networks and Systems*, Springer International Publishing, Cham, 2021, pp. 197–207. doi:10.1007/978-3-030-90318-3_19.

[24] R. Matheus, T. I. Crantschaninov, M. A. Nerling, Interlegis program in Brazil: use of web 2.0, collaborative tools and free software in legislative power, in: Proceedings of the 5th International Conference on Theory and Practice of Electronic Governance, ICEGOV '11, Association for Computing Machinery, New York, NY, USA, 2011, p. 367–368. doi:10.1145/2072069.2072145.

[25] D. Megias, W. Tebbens, L. Bijlsma, F. Santanach, Free technology academy: a european initiative for distance education about free software and open standards, in: Proceedings of the 14th Annual ACM SIGCSE Conference on Innovation and Technology in Computer Science Education, ITiCSE '09, Association for Computing Machinery, New York, NY, USA, 2009, p. 70–74. URL: https://doi.org/10.1145/1562877.1562904. doi:10.1145/1562877.1562904.

[26] J. Barrachina, P. Garrido, F. J. Martinez, F. Repulles, Free software at the education service in accordance with the law, in: Proceedings of the 2012 IEEE Global Engineering Education Conference (EDUCON), 2012, pp. 1–8. doi:10.1109/EDUCON.2012.6201077.

Interactive 3D visualizations for studying combat experiences and life cycles

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Abstract
Studying the dynamics and outcomes of combat engagements is crucial for analyzing military tactics and developing practical recommendations. This article proposes using interactive 3D visualizations and an automated method for selecting rational combat scenarios to thoroughly analyze combat episodes. The approach allows reconstructing the life cycle of a battle in terms of space, time, and involved elements. Key criteria for the visualizations include information completeness and reliability, while indicators encompass the dynamics, effectiveness, and terrain of the engagement. The NATO-standard After Action Review methodology, coupled with mathematical modeling of combat using Lanchester's equations, enables pinpointing mistakes and successful tactics. The article describes visualization system design principles and outlines a phased process for gathering data, building 3D terrain models, and animating unit actions to create an accurate reconstruction. Two combat episodes from the war in Eastern Ukraine in 2015 serve as case studies. The proposed approach facilitates an in-depth analysis of actual battles and the investigation of prospective combat scenarios for diverse purposes, from education to military planning.

Keywords
After Action Review (AAR), 3D visualizations, combat experiences, battle reconstruction, military training and simulation

1. Introduction

Studying the experience of combat engagements is vital for analyzing the actions of opposing forces, identifying shortcomings and successes, and developing military art [1]. However, open information sources often present emotionally and politically charged accounts that lack sufficient detail for a thorough analysis [2, 3].

Seeking to reform its Armed Forces to NATO standards, Ukraine is adopting the After Action Review (AAR) methodology [4]. A key AAR tool is interactive 3D visualization, which accurately reconstructs the course of a battle in time and space [5]. For studying past engagements and forecasting potential scenarios, an automated method of selecting a rational combat scenario with homogeneous forces is proposed [6].

This article aims to substantiate and put forward interactive 3D visualizations for studying combat experiences in the Joint Forces Operation in Eastern Ukraine. It discusses visualization criteria and indicators, outlines the principles and process of creating reconstructions, and demonstrates the approach with two case studies.

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2. Literature review

The use of After Action Reviews and 3D visualizations for analyzing combat actions has garnered increased attention in military research and practice. Holsenbeck [7] described the mental health aspects of the AAR process during a joint aeromedical mission in response to Hurricane Andrew. Darling et al. [8] highlighted how the U.S. Army's Opposing Force (OPFOR) uses rigorous AARs to generate lessons that are fed back into the execution cycle, in contrast to the pro-forma reviews often conducted in corporate settings.

In the context of multinational operations, Conyers et al. [9] reported on Tactical Combat Casualty Care training provided to NATO forces at the Hamid Karzai International Airport, with AARs completed to categorize best practices. Truesdell et al. [10] discussed an expert opinion approach to managing cardiogenic shock, drawing parallels to elite military units' use of AAR to combine adaptability and cohesion.

Autonomous systems have also been a focus of research. Duan et al. [11] developed a hardware-in-loop simulation platform for unmanned aerial vehicle (UAV) autonomous aerial refueling, using an eagle-eye vision mechanism. Karthik et al. [12] proposed a GPS-less 3D inertial routing system for multi-floor indoor positioning during urban combat operations, facilitating after action review.

Regarding visualization system design, Murray [13] described an intelligent tutoring system for commercial games, the Virtual Combat Training Center, which lowers the cost of training while exposing trainees to the full complexities of combat. Rickard et al. [14] emphasized the need for interface standards in Live, Virtual, and Constructive (LVC) fighter aircraft training to ensure a common configuration and enable realistic mission debriefing.

In terms of case studies, Rosenbach and Tien [15] analyzed strategic leadership in the battle of Tal Afar, Iraq, demonstrating how Army officers combined classic and unique aspects of leadership to transform the war's trajectory. Stout et al. [16] reviewed the aeromedical evacuation response to the 1997 airplane crash in Guam, with the AAR resulting in multiple improvements to readiness and procedures.

These studies underscore the importance of detailed data collection, advanced modeling and visualization, and systematic analysis for extracting lessons from combat experiences.

3. Methodology

3.1. Visualization criteria and indicators

The key criterion for assessing 3D visualizations is the degree of their adequacy to the actual combat episode in terms of stages, timeline, and elements [1]. The visual information should aim to maximally approach reality.

Proposed criteria for the interactive 3D visualization of a battle's life cycle include:

1. *Information completeness and reliability*
   Sufficient, accurate data must be gathered from multiple sources to reconstruct the battle in detail. This includes tactical maps, unit positions, stage-by-stage descriptions, communications, and outcomes. Contradictory or missing information should be rectified through additional research and participant interviews.
2. *Battle dynamics*
   The visualization should capture the flow of the engagement, including unit movements, firing, maneuvering, and changes in control over time. Dynamic elements such as explosions, smoke, and vehicle damage enhance realism.
3. *Effectiveness of combat actions*
   Indicators of effectiveness include casualties inflicted and sustained, ground gained or lost, and objectives achieved by each side. These can be represented visually and quantitatively.

4. *Terrain characteristics*
   The 3D model should accurately depict the landscape, vegetation, structures, and fortifications where the battle occurred. Line of sight, cover and concealment, and mobility corridors influence tactics and outcomes. Geospatial anchoring aligns the virtual and real-world terrain.

Measures of information content range from sufficient, to partial yet adequate, partial and inadequate, and insufficient or missing data. Analysts must carefully assess available sources and work closely with military experts to construct a credible visualization.

3.2. After Action Review and Mathematical Modeling

NATO's AAR methodology focuses on evaluating the outcome of an event by answering three main questions [1]:

1. **What happened during the combat episode?** This involves establishing the facts, sequence of events, and overall outcome based on reports, interviews, and other records. An initial timeline and narrative are constructed.
2. **Why did the episode unfold in this manner?** Analysts probe the causes and contributing factors behind key decisions and actions by each side. This includes assessing the use of terrain, maneuver, fires, leadership, and adaptability. Participant perspectives are elicited to uncover rationale and mindset.
3. **How can the outcome be improved?** Insights from the preceding analysis are distilled into lessons and recommendations to address gaps in planning, execution, and capability. These may span doctrine, organization, training, materiel, leadership, personnel, and facilities. The emphasis is on actionable, specific measures.

Mathematical modeling of combat using Lanchester's equations complements the AAR by quantifying the dynamics and outcomes of engagements. Lanchester models represent attrition between two homogeneous forces as a system of ordinary differential equations [17]:

$$\begin{aligned} \frac{dm}{dt} &= -\alpha n(t) \\ \frac{dn}{dt} &= -\beta m(t) \end{aligned} \tag{1}$$

where $m(t)$ and $n(t)$ are the force levels of the two sides at time t, and α and β are attrition rate coefficients representing the effectiveness of each unit against the opposing side.

By considering different initial force ratios, attrition rates, and engagement termination conditions, analysts can explore the sensitivity of outcomes to various factors. This enables quantitative evaluation of alternate courses of action and highlights the leverage points for achieving desired results.

Lanchester models have been extended to incorporate heterogeneous forces, spatial effects, morale, and logistics [18]. However, their core insight remains valuable: the relationship between attrition rates and force ratios fundamentally shapes the dynamics of combat.

The AAR findings can inform the selection of appropriate Lanchester model parameters to represent a given battle. Conversely, modeling results can guide inquiry into the drivers of observed outcomes during the AAR process. This symbiotic relationship strengthens the analytic rigor of both methods.

4. Visualization system design

A combat visualization system typically consists of a graphics pipeline and a set of control programs (figure 1). The pipeline involves the formation, geometric processing, and rasterization of reliable data. Control programs handle pipeline initialization and interaction with the external environment.

Key requirements for landscape visualization algorithms include minimizing central processor load to free up resources for combat episode modeling. Techniques such as discarding invisible terrain

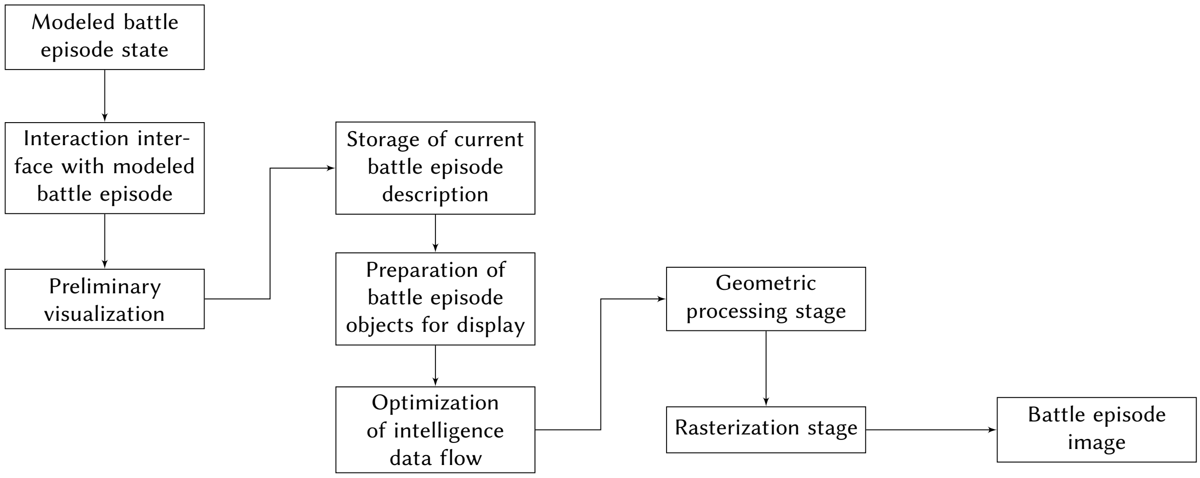

Figure 1: Battle episode visualization system.

sections and reducing detalization of distant areas help to optimize performance. The use of regular or irregular grid-based methods, like Fast Terrain Rendering Using Geometrical MipMapping [19] or Thatcher Ulrich's Chunked LOD [20], is common.

Several principles guide the design of an effective combat visualization system:

- Modularity: The system should consist of loosely coupled components with well-defined interfaces. This allows for iterative development, testing, and extension of individual modules without disrupting the overall architecture.
- Scalability: The visualization framework needs to accommodate scenarios of varying size and complexity, from small unit actions to large scale operations. Techniques such as level-of-detail rendering and adaptive scheduling can help maintain interactive performance.
- Interoperability: The system must interface with a range of data sources, combat simulations, and command and control systems. Adherence to standards such as Distributed Interactive Simulation (DIS) and High Level Architecture (HLA) promotes integration with existing and future military systems.
- User-centricity: The user interface should be intuitive and tailored to the needs of different stakeholders, such as commanders, analysts, and trainees. Customizable views, query tools, and playback controls enable users to effectively explore and manipulate the visualization.
- Extensibility: The design should allow for the integration of new types of data, entities, and behaviors as modeling and simulation capabilities advance. This may include support for higher-fidelity physics, artificial intelligence, and virtual/augmented reality technologies.

5. Visualization process

Creating an interactive 3D visualization of a combat episode involves several stages [1]:

1. **Gathering and analyzing information from various sources to reconstruct the battle in sufficient detail.** This includes tactical maps, operations orders, unit positions, communications logs, imagery, after action reports, and participant interviews. A systematic data collection plan helps ensure completeness and identifies gaps requiring further research.
2. **Building a 3D model of the terrain using a digital elevation model and overlaying relevant features such as vegetation, roads, rivers, bridges, buildings, and fortifications.** High-resolution remote sensing data, maps, and site surveys contribute to an accurate environmental representation. Terrain analysis tools can derive mobility corridors, intervisibility lines, and avenues of approach.

3. **Placing 3D models of personnel, vehicles, and equipment according to their initial positions on the tactical map.** Models may be based on standard military assets or specifically designed to match unique features observed in the battle. Attention to details such as unit markings, camouflage patterns, and weathering adds realism.
4. **Animating the actions of each entity over the course of the battle based on the collected data.** This includes movement along routes, changes in formation, deployment of forces, firing of weapons, detonation of ordnance, and incapacitation or destruction of assets. Timing of actions is synchronized with the battle narrative to reflect the dynamism of combat.
5. **Integrating additional elements to enhance the immersion and information content of the visualization.** These may include audio recordings of commands and radio traffic, video clips from cameras or unmanned systems, graphical overlays showing unit boundaries and phase lines, and data displays of ammunition expenditure, casualties, and system status.
6. **Rendering the complete visualization and packaging it for interactive display on various platforms.** Users can control the viewpoint, playback speed, and information layers to suit their analytic needs. The visualization becomes a key artifact supporting the AAR process, enabling participants to review the battle from multiple perspectives.

As a concrete example, the Interactive 3D Visualization Constructor software suite, developed at the National Technical University “Kharkiv Polytechnic Institute”, was employed to reconstruct two combat episodes from the war in Eastern Ukraine [21].

For each case, data was first collected from open sources, tactical maps, and surveys of participants. 3D terrain was built from digital elevation models, and features such as trees, roads, and buildings were added based on overhead imagery. 3D models of Ukrainian and Russian equipment, such as tanks, infantry fighting vehicles, and anti-tank guided missile systems, were placed at their initial locations.

The movement of each vehicle and unit was animated over time based on the battle records. Engagements, artillery strikes, and destruction of assets were recreated, with special effects like explosions, smoke, and flying debris. Sounds of gunfire and radio communications were layered over the visual scene.

The resulting visualizations were rendered and packaged for viewing on desktop and mobile devices. Users could freely move the camera to observe the action from any angle, pause and resume the playback, and toggle information overlays showing unit positions, engagement ranges, and kill counts.

These interactive 3D visualizations supported detailed AAR sessions with the participants and military students. By virtually stepping through the battles, reviewers could identify decisive moments, discuss the rationale behind decisions, and assess the application of tactics, techniques and procedures. Alternative actions could be explored by manipulating the visualization, fostering counterfactual reasoning.

Beyond AAR, the visualizations served as case studies for professional military education, exposing students to the complexity and chaos of modern combat. By studying the battles from multiple viewpoints, learners developed an appreciation for the challenges faced by commanders and the importance of factors such as terrain, timing, and coordination.

The 3D visualizations were also used to brief senior leaders on the operational situation and outcomes. The realistic and immersive nature of the presentations facilitated understanding and communication of the battles’ significance.

6. Case studies

The previously described methodology was applied to reconstruct two combat episodes from the war in Eastern Ukraine [21]:

- The defense of the “Seroga” strongpoint near Sanzharivka by Ukrainian mechanized and tank units on January 28, 2015.
- The assault on Logvinove by Ukrainian mechanized and tank units on February 12, 2015.

6.1. Defense of the "Seroga" strongpoint

The first case study examines the defense of the "Seroga" strongpoint by elements of a Ukrainian mechanized brigade against a Russian-backed separatist assault on January 28, 2015. The strongpoint, located near the village of Sanzharivka in Donetsk Oblast, consisted of a company-sized force equipped with T-64 tanks, BMP-2 infantry fighting vehicles (IFVs), and 82mm mortars.

At approximately 0400 hours, the separatists launched an attack on the strongpoint with a battalion-sized force, supported by artillery and multiple launch rocket systems (MLRS). The initial assault was repelled by direct fire from the Ukrainian tanks and IFVs, which inflicted heavy casualties on the advancing infantry and disabled several enemy vehicles.

However, the separatists regrouped and commenced a sustained bombardment of the Ukrainian positions with 122mm howitzers and 120mm mortars. This fire destroyed several Ukrainian vehicles and forced the defenders to seek cover in their trenches and bunkers. Under the cover of this fire, the separatists maneuvered a company of tanks and IFVs around the Ukrainian right flank, threatening to cut off their withdrawal.

Recognizing the danger, the Ukrainian commander ordered a fighting withdrawal to a secondary defensive position 2 km to the rear. The Ukrainian tanks provided covering fire while the IFVs and dismounted infantry conducted a bounding overwatch movement to the fallback position. Despite taking additional casualties from enemy fire, the Ukrainians successfully disengaged and occupied their new defenses by 0900 hours.

The visualization of this battle was created using the Interactive 3D Visualization Constructor software. Tactical maps and overhead imagery were used to build a detailed 3D terrain model of the strongpoint and surrounding area, including the village, fields, roads, and treelines. 3D models of the Ukrainian T-64 tanks, BMP-2 IFVs, trucks, and 82mm mortars were placed at their initial positions based on the commander's sketch and participant interviews. Separatist T-72 tanks, BMP-1 IFVs, and MLRS were similarly modeled and positioned.

The movement of each vehicle was animated based on the tactical map and narrative of the battle. Key events such as the initial assault, artillery strikes, flank attack, and withdrawal were visualized with appropriate effects and sounds. The user could view the battle from any angle, including from the perspective of individual vehicles or commanders, and pause the action to examine the situation in detail.

The AAR of this battle identified several key lessons:

- The importance of well-prepared defensive positions and interlocking fields of fire in repelling an attack by a numerically superior force. The Ukrainian tanks and IFVs were able to inflict heavy casualties on the separatists due to their dug-in positions and coordinated fire plan.
- The decisive role of artillery and MLRS in suppressing defensive positions and enabling maneuver. The separatists' concentrated and sustained bombardment forced the Ukrainians to seek cover and degraded their ability to repel the flank attack.
- The value of a timely and organized withdrawal in the face of an overwhelming attack. By displacing to a secondary position before becoming decisively engaged, the Ukrainian commander preserved his force and avoided encirclement.
- The criticality of situational awareness and rapid decision-making in a dynamic battle. The Ukrainian commander had to quickly assess the situation, anticipate enemy actions, and issue clear orders to his subordinates to maintain cohesion and effectiveness.

These lessons were incorporated into subsequent training and doctrine for Ukrainian mechanized units. The 3D visualization became a valuable tool for educating new commanders and soldiers on the realities of high-intensity combat against a sophisticated opponent.

6.2. Assault on Logvinove

The second case study focuses on the Ukrainian assault to retake the village of Logvinove from separatist forces on February 12, 2015. Logvinove, located along the strategic Debaltseve-Artemivsk highway in

Donetsk Oblast, had been captured by the separatists two days prior, cutting off the main supply route to Ukrainian forces defending the Debaltseve salient.

The Ukrainian command mobilized a tank company and a mechanized infantry company to assault Logvinove and reopen the highway. The tanks, a mix of T-64BVs and T-64BMs, were tasked with leading the attack and destroying enemy armor, while the mechanized infantry in BMP-2s would clear the village and secure the flanks.

At 1000 hours, the Ukrainian force departed its assembly area and began advancing towards Logvinove along the highway. Approximately 1 km from the village, the lead tanks came under fire from separatist T-72s and anti-tank guided missiles (ATGMs) positioned on the high ground to the north. Two Ukrainian tanks were quickly disabled, forcing the remainder to seek cover and engage the enemy armor at standoff range.

As the tank battle unfolded, the Ukrainian mechanized infantry dismounted and began clearing the outlying buildings of Logvinove. They immediately came under heavy small arms and RPG fire from separatist infantry occupying prepared positions in the village. The fighting devolved into a brutal close-quarters battle, with the Ukrainians using grenades and armored vehicle support to dislodge the defenders house by house.

By 1400 hours, the Ukrainians had cleared the southern half of Logvinove and advanced to the center of the village. However, they were unable to progress further due to well-coordinated separatist resistance and the threat of encirclement. Running low on ammunition and fuel, and with night falling, the Ukrainian commander ordered a withdrawal to avoid becoming decisively engaged. The assault had failed to completely clear Logvinove or reopen the highway.

To visualize this battle, the terrain team built a highly detailed 3D model of Logvinove and the surrounding area using tactical maps, UAV imagery, and photographs. Particular attention was paid to modeling the buildings, streets, and defensive positions in the village. 3D models of the Ukrainian T-64 tanks and BMP-2s, as well as the separatist T-72s, ATGMs, and infantry were created and placed at their starting locations.

The assault was animated in phases, showing the initial Ukrainian advance, separatist ambush, tank battle, village clearance, and withdrawal. Cameras were placed in the turrets of the tanks and BMP-2s to give the viewer a sense of the limited visibility and situational awareness of the vehicle crews. Sounds of tank and small arms fire, RPG launches, and radio communications were synced with the action to create an immersive experience.

The AAR of the Logvinove assault surfaced several important lessons:

- The difficulty of attacking a well-defended urban area without significant numerical superiority and combined arms support. The separatists' interlocking fields of fire, prepared positions, and coordinated resistance stymied the Ukrainian advance and inflicted heavy casualties.
- The vulnerability of armor to ATGMs in complex terrain. The separatist Konkurs and Fagot ATGMs, positioned on high ground flanking the approach to Logvinove, quickly knocked out several Ukrainian tanks and forced the remainder to seek cover, disrupting the momentum of the assault.
- The importance of reconnaissance and intelligence preparation of the battlefield (IPB) prior to an attack. The Ukrainians lacked detailed information on the separatist positions, strength, and dispositions in Logvinove, leading to an underestimation of the defense and a piecemeal commitment of forces.
- The challenge of sustaining an assault without robust logistics and force rotation. The Ukrainian attack faltered in part due to the exhaustion of ammunition and fuel, and the inability to replace personnel and vehicle losses, as the battle progressed.

These hard-won insights were applied to refine Ukrainian urban warfare tactics, adjust force compositions and task organizations, and improve the planning and execution of future offensive operations. The Logvinove visualization became a cautionary case study, illustrating the complex dynamics of combat in built-up areas against a determined and well-equipped enemy.

Both the Sanzharivka and Logvinove case studies demonstrate the power of interactive 3D visualization to reconstruct and analyze complex combat episodes. By creating an immersive and data-driven representation of the battle space, these visualizations enable military professionals to explore the multidimensional factors that shape the course of engagements, from the decisions of individual commanders to the effects of weapon systems and terrain.

Moreover, by subjecting the visualizations to structured AAR processes, practitioners can derive actionable lessons learned and identify best practices for future operations. The integration of 3D visualization with established analytic frameworks like AAR creates a potent tool for military learning and adaptation.

As the fidelity and sophistication of modeling and simulation technologies advance, the potential applications of interactive 3D visualization in the military domain will only expand. From mission planning and rehearsal to after-action review and training, immersive visualizations will play an increasingly central role in preparing armed forces for the challenges of 21st century warfare.

7. Conclusion

Interactive 3D visualization, coupled with AAR methodology and mathematical combat modeling, provides a powerful tool for analyzing past combat episodes and testing prospective scenarios. The proposed approach enables an accurate reconstruction of battles in space and time, helping to identify mistakes and successful tactics.

The case studies of the Sanzharivka strongpoint defense and Logvinove assault demonstrate the value of 3D visualization in understanding the complex dynamics of modern combat. By collecting and integrating data from multiple sources, modeling the terrain and units in detail, and animating the flow of the battle, these visualizations create an immersive and data-driven representation of the engagement.

Subjecting the visualizations to structured AAR processes enables military professionals to explore the key factors that shape the outcomes of battles, from decisions and maneuvers to the effects of weapon systems and terrain. By deriving lessons learned and best practices, practitioners can adapt tactics, techniques, and procedures for future operations.

The methodology presented in this article can benefit a wide range of military applications, from mission planning and rehearsal to education and training. Future research may further explore the integration of 3D visualization with other analytic methods and data sources, such as combat logs, equipment sensors, and participant interviews. The development of automated tools for data ingestion, entity behavior modeling, and scenario generation could streamline the visualization process and allow for more rapid and flexible analysis.

The use of virtual and augmented reality technologies may also enhance the immersion and interactivity of combat visualizations, enabling users to more naturally explore and manipulate the battle space. Collaborative visualization environments could allow geographically distributed teams to jointly analyze and discuss combat episodes, facilitating shared understanding and decision-making.

References

[1] I. V. Barkatov, V. P. Varakuta, V. S. Farafonov, V. O. Tiurin, S. S. Honcharuk, A. A. Lozko, Using Interactive Three-Dimensional Visualizations to Study Combat Experiences of Units in the Joint Forces Operation, in: Science and Technology of the Air Force of Ukraine, volume 3, 2021. doi:10.30748/zhups.2021.69.04.
[2] Y. Butusov, War and guilt, 2021. URL: https://gazeta.zn.ua/internal/voyna-i-vina-_.html.
[3] O. Yarchuk, Battle Analysis. Debaltseve Bulge 26.01–02.02.2015, 2015. URL: http://oyblogg.blogspot.de/p/blog-page_4.html.
[4] After-Action Review, 2024. URL: https://drive.google.com/file/d/1oM2fTGUtOwD46AHNKIVOg844bBKHfwhn/view.

[5] V. S. Farafonov, I. V. Barkatov, S. A. Babak, Application of Interactive 3D Tactical Field Model to Study Combat Experience in the Anti-Terrorist Operation Zone, in: Academic Support for Service and Combat Activities of the National Guard of Ukraine, 2017, p. 144.
[6] I. V. Barkatov, V. S. Farafonov, S. O. Holovach, Development of an Interactive 3D Tactical Field Model to Enhance the Effectiveness of Tactical and Tactical-Special Disciplines Classes in Reserve Officers Training, in: Prospects for the Development of Automated Command and Control Systems and Geoinformation Systems, 2015, p. 144.
[7] L. Holsenbeck, Joint Task Force Andrew: The 44th medical brigade Mental Health Staff Officer's after action review, Military Medicine 159 (1994) 186–191. doi:10.1093/milmed/159.3.186.
[8] M. Darling, C. Parry, J. Moore, Learning in the thick of it, Harvard Business Review 83 (2005) 84–92+192.
[9] K. Conyers, A. B. Gillies, C. Sibley, C. McMullen, M. A. Remley, S. Wence, J. M. Gurney, Where There's a War, There's a Way: A Brief Report on Tactical Combat Casualty Care Training in a Multinational Environment, Journal of special operations medicine : a peer reviewed journal for SOF medical professionals 23 (2023) 130–133. doi:10.55460/WKSE-6PVS.
[10] A. G. Truesdell, B. Tehrani, R. Singh, S. Desai, P. Saulino, S. Barnett, S. Lavanier, C. Murphy, Expert opinion: 'Combat' approach to cardiogenic shock, Interventional Cardiology: Reviews, Research, Resources 13 (2018) 81–86. doi:10.15420/icr.2017:35:3.
[11] H. Duan, Q. Zhang, Y. Deng, X. Zhang, Biologically eagle-eye-based autonomous aerial refueling for unmanned aerial vehicles, Yi Qi Yi Biao Xue Bao/Chinese Journal of Scientific Instrument 35 (2014) 1450–1457.
[12] B. Karthik, M. Usila, M. Sundararajan, GPS less 3d inertial routing system for multi-floor indoor positioning during urban combat operations, Journal of Chemical and Pharmaceutical Sciences 9 (2016) S283–S286.
[13] W. R. Murray, Intelligent tutoring systems for commercial games: The virtual combat training center tutor and simulation, in: Proceedings of the 2nd Artificial Intelligence and Interactive Digital Entertainment Conference, AIIDE 2006, 2006, pp. 66–71.
[14] R. N. Rickard, W. R. Bennett Jr., C. Colegrove, Development of fighter aircraft live, virtual and constructive (LVC) interface standards, in: Fall Simulation Interoperability Workshop, 2013 Fall SIW, 2013, pp. 250–260.
[15] E. B. Rosenbach, J. Tien, How the west was won: Strategic leadership in Tal Afar, in: Military Leadership: In Pursuit of Excellence, Taylor and Francis, 2018, pp. 223–232. doi:10.4324/9780429495007.
[16] L. R. Stout, J. R. Jezior, L. P. Melton, J. A. Walker, M. L. Brengman, S. T. Neumeier, R. L. Smith, C. A. Vanfosson, T. E. Knuth, J. B. Holcomb, L. C. Cancio, Wartime burn care in Iraq: 28th Combat Support Hospital, 2003, Military Medicine 172 (2007) 1148–1153. doi:10.7205/MILMED.172.11.1148.
[17] R. L. Helmbold, A. S. Rehm, "The influence of the numerical strength of engaged forces in their casualties," by M. Osipov, Naval Research Logistics (NRL) 42 (1995) 435–490. doi:10.1002/1520-6750(199504)42:3<435::AID-NAV3220420308>3.0.CO;2-2.
[18] J. T. Christian, An Examination of Force Ratios, Monograph, U.S. Army Command and General Staff College Fort Leavenworth United States, 2019. URL: https://apps.dtic.mil/sti/citations/AD1083211.
[19] W. H. de Boer, Fast Terrain Rendering Using Geometrical MipMapping, 2000. URL: https://www.flipcode.com/archives/article_geomipmaps.pdf.
[20] T. Ulrich, Rendering Massive Terrains using Chunked Level of Detail Control, in: Super-size It! Scaling Up to Massive Virtual Worlds, The Eurographics Association, 2002, pp. 211–224. URL: http://tulrich.com/geekstuff/sig-notes.pdf.
[21] I. V. Barkatov, V. S. Farafonov, S. S. Dychko, The War in Donbas 2014-2018, in: Proceedings of the IV All-Ukrainian Scientific Military-Historical Conference, National Military History Museum of Ukraine, 2019.

Methodical foundations and implementation strategies for virtual reality in professional training of vocational higher education students

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Abstract

This paper presents a comprehensive exploration of the methodical foundations and implementation strategies for integrating virtual reality (VR) technologies in the professional training of students in vocational higher education. A detailed model for VR integration is presented, accompanied by an in-depth discussion of pedagogical conditions and evidence-based recommendations for effective use. The paper extensively examines the potential of virtual workshops and laboratories to enhance practical skills development, with a focus on industry-specific applications. Furthermore, it delves into the challenges and considerations for VR adoption, including technological, pedagogical, and institutional factors. The findings demonstrate that thoughtful VR integration, when part of a holistic educational approach, can significantly improve student engagement, motivation, and acquisition of professional competencies. The paper also discusses the implications of VR integration for curriculum design, assessment methods, and the changing role of educators in technology-enhanced learning environments.

1. Introduction

The rapid advancement of digital technologies is transforming educational practices across all sectors, with immersive technologies at the forefront of this revolution [1]. In vocational higher education, there is growing interest in using virtual reality (VR) to enhance the professional training of students [2]. VR offers unique affordances for creating realistic simulations of workplace environments, allowing students to practice skills in safe, controlled settings, and providing experiences that would be difficult or impossible to replicate in traditional educational contexts [3].

The potential benefits of VR in education are manifold. It can provide immersive, experiential learning opportunities that bridge the gap between theory and practice [4, 5]. VR simulations can expose students to a wide range of scenarios and equipment, some of which may be too costly, dangerous, or rare to encounter in physical training environments. Moreover, VR can enable repeated practice and instant feedback, potentially accelerating the learning process and improving skill retention [6].

However, the effective integration of VR into vocational curricula is not without challenges. It requires careful consideration of pedagogical approaches, technological infrastructure, institutional readiness, and the specific needs of different vocational fields [6]. There are also concerns about the potential drawbacks of VR, such as the risk of cognitive overload, the need for significant initial investment, and the importance of maintaining a balance with hands-on, real-world training.

This paper aims to provide comprehensive methodical foundations for implementing VR in the professional training of vocational higher education students. We present a detailed model for VR integration, outline key pedagogical conditions, and offer evidence-based recommendations for educators and institutions.

The research is motivated by several factors:

- The need to bridge the persistent gap between theoretical knowledge and practical skills in vocational education

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- The potential of VR to provide safe, cost-effective training for high-risk or resource-intensive professions
- The growing demand from industries for graduates with advanced technological skills
- The opportunity to increase student engagement and motivation through immersive learning experiences
- The need for vocational institutions to stay at the forefront of educational innovation

2. Background

2.1. Virtual reality in education

Virtual reality refers to computer-generated simulations of three-dimensional environments that can be interacted with in seemingly real or physical ways [7]. In educational contexts, VR allows for immersive, experiential learning through a variety of mechanisms:

- Creation of realistic workplace simulations that replicate the look, feel, and functionality of actual professional environments
- Visualization of complex processes and systems that may be difficult to observe or understand in the real world
- Hands-on practice of skills in safe, controlled environments where mistakes have no real-world consequences
- Gamified learning experiences that increase engagement and motivation
- Virtual field trips to locations or facilities that would be impractical to visit physically
- Collaborative virtual spaces where students can work together on projects regardless of physical location

The immersive nature of VR can lead to a sense of presence, where users feel as if they are actually in the simulated environment. This can enhance the emotional and cognitive engagement of learners, potentially leading to deeper understanding and better retention of information [6, 8].

Studies have shown that VR can increase student engagement, motivation, and knowledge retention compared to traditional instructional methods [6]. For example, research in medical education has demonstrated that VR simulations can improve surgical skills and reduce training time [9]. In engineering education, VR has been used to enhance spatial understanding and design skills [10].

However, challenges remain around several key issues:

- The cost of high-quality VR systems may limit widespread adoption, as they can be expensive
- Developing and maintaining VR systems requires specialized technical expertise
- Complex VR environments may increase cognitive load, potentially overwhelming some learners, particularly novices
- Extended use of VR can cause physical discomfort or motion sickness for some users
- Ensuring equitable access to VR technology for all students can be difficult

These challenges underscore the need for careful planning and implementation when integrating VR into educational programs.

2.2. Professional training in vocational higher education

Vocational higher education aims to prepare students for specific occupations through a combination of theoretical knowledge and practical skills development. Key aspects of vocational education include:

- Hands-on training in job-specific competencies that directly relate to workplace tasks
- Industry partnerships that provide real-world exposure and work-based learning opportunities

- Focus on employability and career readiness, including soft skills development
- Alignment of curriculum with industry standards and emerging technologies
- Emphasis on problem-solving and critical thinking in job-relevant contexts
- Integration of theory and practice through applied learning approaches

Traditional methods of vocational training often involve a combination of classroom instruction, laboratory work, workshops, and internships. While these approaches have proven effective, they can be limited by factors such as equipment costs, safety concerns, and the ability to replicate diverse workplace scenarios [11].

VR offers promising applications in vocational training by allowing for realistic simulations of workplace scenarios and equipment that may be difficult, dangerous, or expensive to access in physical settings [12, 13]. For example:

- In healthcare education, VR can simulate complex medical procedures without risk to patients
- In engineering, VR can allow students to interact with virtual prototypes and test designs
- In hospitality training, VR can recreate diverse customer service scenarios
- In construction education, VR can provide safe exposure to hazardous work environments

However, it is crucial to recognize that VR should complement rather than replace traditional hands-on learning. The tactile experience of working with real tools and materials remains an essential component of vocational training. Therefore, the integration of VR must be done thoughtfully, as part of a blended learning approach that combines the best of both virtual and physical training methods.

3. Model for VR integration

Based on a comprehensive analysis of pedagogical literature and current best practices, we propose a detailed model for integrating VR into professional training programs in vocational higher education (figure 1). This model consists of five interconnected components, each playing a crucial role in ensuring effective and purposeful use of VR technology.

3.1. Goal block

The foundation of effective VR integration lies in clear, well-defined learning objectives that align VR activities with overall curriculum goals and industry skill requirements. This component involves:

- Conducting a thorough needs analysis to identify areas where VR can add significant value
- Collaborating with industry partners to ensure relevance to current workplace demands
- Defining specific, measurable, achievable, relevant, and time-bound (SMART) objectives for VR-enhanced learning
- Identifying the particular skills or competencies that VR is best suited to develop
- Considering both technical skills and soft skills (e.g., communication, problem-solving) in objective setting

Examples of well-defined goals might include:

- Developing proficiency in operating specific machinery or equipment
- Improving decision-making skills in high-pressure scenarios
- Enhancing spatial awareness and design capabilities
- Increasing confidence in performing complex procedures

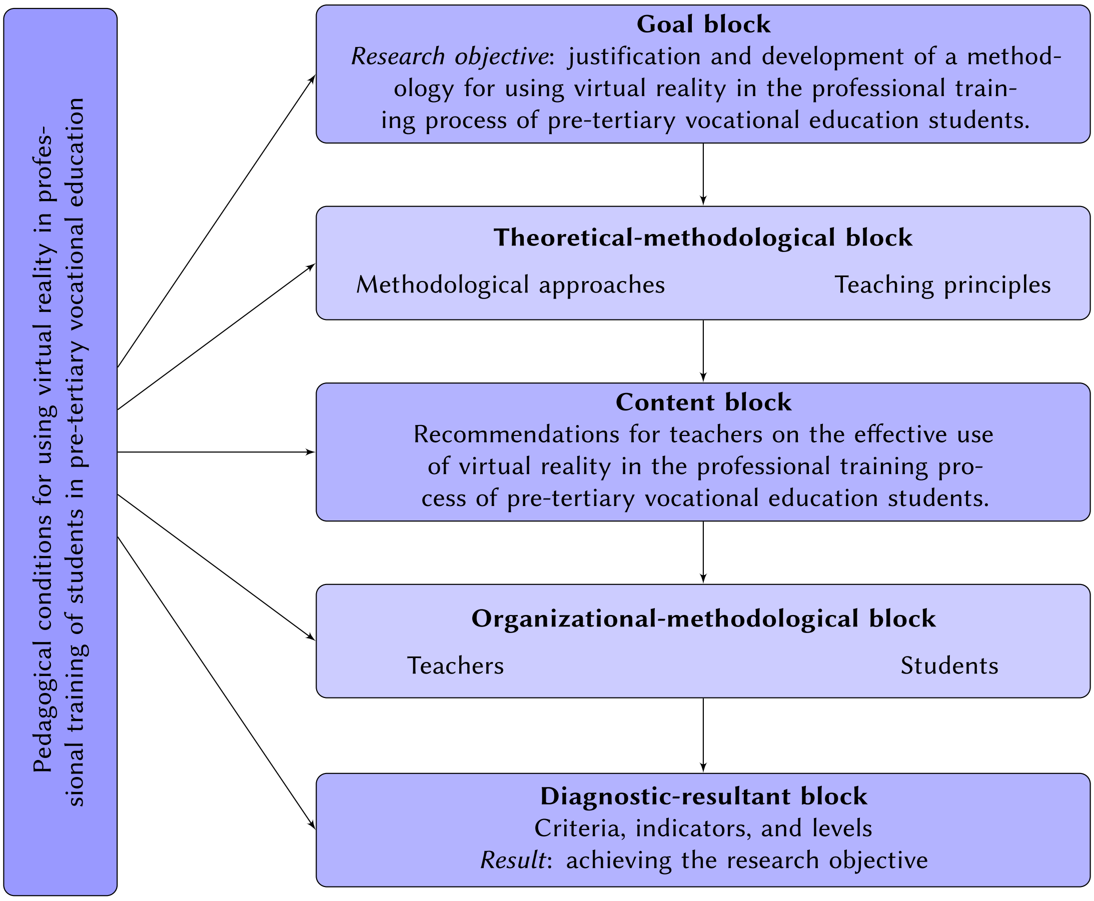

Figure 1: Comprehensive model for integrating VR in vocational higher education.

3.2. Theoretical-methodological block

The pedagogical framework should draw on established learning theories while using the unique affordances of VR. Key principles and strategies include:

- *Experiential learning*, incorporating Kolb's experiential learning cycle in VR simulations, where students engage in experiencing, reflecting, conceptualizing, and actively experimenting
- *Situated learning* by designing authentic contexts that mirror real-world applications of knowledge
- *Scaffolded skill development* through a sequence of VR activities that become progressively more complex and challenging
- *Collaborative learning*, offering opportunities for peer interaction and teamwork in virtual environments
- *Constructivist approaches* that prompt students to actively build knowledge through exploration and problem-solving
- *Multimodal learning*, using VR's visual, auditory, and kinesthetic features to address various learning styles
- *Adaptive learning*, employing data analytics from VR systems to customize learning experiences based on individual student performance [14]

3.3. Content block

VR learning content and activities should be carefully designed to achieve defined learning objectives while taking full advantage of the technology's capabilities:

- *Realistic modeling*, creating high-fidelity representations of workplace environments, equipment, and processes
- *Interactive elements*, designing intuitive interactions that allow for active learning and experimentation
- *Scenario-based learning*, developing a range of scenarios that reflect real-world challenges and decision points
- *Gamification*, incorporating game-like elements such as points, levels, and challenges to increase engagement
- *Feedback mechanisms*, implementing immediate, constructive feedback to guide student learning
- *Difficulty scaling*, creating content with adjustable levels of complexity to accommodate different skill levels
- *Cultural sensitivity*, ensuring content is inclusive and respectful of diverse backgrounds
- *Accessibility features*, incorporating options to accommodate students with different abilities

3.4. Organizational-methodological block

Effective implementation of VR in the curriculum requires careful planning and execution:

- *Technology infrastructure*, ensuring adequate hardware, software, and network capabilities to support VR systems
- *Instructor training*, providing comprehensive professional development for faculty on both technical and pedagogical aspects of VR
- *Student orientation*, developing structured introduction sessions to familiarize students with VR technology and safety protocols
- *Integration with curriculum*, seamlessly incorporating VR activities into existing course structures and learning pathways
- *Support systems*, establishing technical support mechanisms for troubleshooting and maintenance
- *Scheduling and access*, creating efficient systems for student access to VR resources, especially if equipment is limited
- *Health and safety*, implementing guidelines to ensure safe and comfortable use of VR equipment
- *Ethical considerations*, addressing privacy concerns and data management in VR learning environments

3.5. Diagnostic-resultant block

Ongoing assessment and evaluation are crucial to refine and improve VR implementation:

- *Learning outcomes*, measuring achievement of defined learning objectives through appropriate assessment methods
- *User experience*, gathering detailed student and instructor feedback on the usability and effectiveness of VR activities
- *Engagement metrics*, analyzing data on student participation, time spent, and progress in VR environments
- *Comparative analysis*, conducting studies to compare outcomes between VR-enhanced and traditional learning approaches
- *Skill transfer*, assessing the degree to which skills learned in VR translate to real-world performance
- *Cost-benefit analysis*, evaluating the return on investment in terms of educational outcomes and resource utilization
- *Longitudinal studies*, tracking long-term impacts on student career readiness and professional success
- *Continuous improvement*, using evaluation data to iteratively refine VR content, implementation strategies, and pedagogical approaches

4. Pedagogical conditions for effective VR use

Our analysis identified two key pedagogical conditions that should be established for effective use of VR in professional training. These conditions are crucial for creating an environment where VR can truly enhance the learning experience and contribute to the development of professional competencies.

4.1. Motivation for professional activities

Enhancing student motivation for their chosen profession is a critical factor in the success of vocational education. VR activities should be carefully designed to increase this motivation by:

- Providing realistic previews of workplace environments, offering immersive experiences that give students a tangible sense of their future work settings, helping to solidify their career choices and increase commitment to their studies
- Allowing experimentation with job tasks in low-stakes settings, enabling students to try out various professional tasks without real-world consequences, building confidence and reducing anxiety about future job performance
- Demonstrating relevance of theoretical concepts to practice, bridging the gap between abstract concepts and practical application, helping students understand the importance of their theoretical studies
- Gamifying skill development, incorporating game-like elements such as challenges, rewards, and progress tracking to make skill acquisition more engaging and enjoyable
- Facilitating goal-setting and progress monitoring, helping students set personal learning goals and track their progress, fostering a sense of achievement and growth
- Enabling exploration of career paths, allowing students to experience different specializations within their field, aiding them in making informed decisions about their career trajectories
- Fostering a sense of professional identity, using immersive experiences in professional settings to help students begin to see themselves as members of their chosen profession, increasing motivation to excel

4.2. Integration of VR methodology

To ensure that VR is not just a novelty but an integral and effective part of the learning process, a clear methodology for VR integration should be developed and implemented:

- Aligning VR activities with curriculum learning objectives, ensuring each VR experience has a clear purpose and is directly linked to specific learning outcomes defined in the curriculum
- Providing adequate technical and pedagogical support for instructors, offering comprehensive training and ongoing support to help educators effectively incorporate VR into their teaching practices
- Ensuring accessibility and ease-of-use for all students, designing VR systems with inclusivity in mind to accommodate different learning styles and physical abilities
- Combining VR with other teaching methods in a blended approach, using VR to complement, not replace, other effective teaching methods, creating a balanced and diverse learning experience
- Developing assessment strategies for VR-based learning, creating new methods of evaluation to accurately assess skills and knowledge gained through VR experiences
- Creating a feedback loop for continuous improvement, regularly collecting and analyzing data from VR sessions to inform ongoing refinement of the technology and its implementation
- Integrating VR across the curriculum, weaving VR throughout the educational program where appropriate, rather than treating it as an isolated tool
- Fostering a culture of innovation and technological literacy, encouraging both students and faculty to embrace new technologies and continuously explore their potential in education

- Developing guidelines for appropriate use, establishing clear protocols for when and how VR is used, ensuring it is employed where it adds the most value to the learning experience
- Collaborating with industry partners, engaging with employers to ensure VR simulations reflect current industry practices and technologies

5. Virtual workshops and laboratories

A particularly promising application of VR in vocational training is the creation of virtual workshops and laboratories [15, 16]. These immersive environments offer unique opportunities for skill development and experiential learning [17, 18]. In virtual workshops and labs, students can:

- Practice using specialized equipment and tools, gaining familiarity with a wide range of industry-specific tools and machinery, including those that might be too expensive or dangerous for frequent hands-on use
- Conduct experiments and simulations, exploring complex scientific processes or engineering principles in detail, with the ability to manipulate variables and observe outcomes in real-time
- Troubleshoot realistic workplace scenarios, encountering and solving common (and uncommon) problems they might face in their future careers, developing critical thinking and problem-solving skills
- Collaborate on team projects, using virtual environments to facilitate group work and allowing students to collaborate on complex tasks regardless of physical location
- Explore dangerous or hard-to-access environments, simulating hazardous conditions or remote locations to gain valuable experience without risk
- Visualize abstract concepts, rendering complex theories or microscopic processes in 3D to make them easier to understand and remember

Key features of effective virtual workshops include:

- High-fidelity 3D modeling of real-world environments, ensuring the virtual environment is realistic and transferable to real-world skills
- Physics-based interactions with objects and machinery, accurately simulating how objects behave and interact to enhance the learning experience
- Customizable scenarios of varying complexity, providing the ability to adjust difficulty levels for scaffolded learning experiences
- Data collection and analysis tools, allowing students to track their performance and learn from their actions
- Instructor monitoring and intervention capabilities, enabling teachers to observe student activities and provide guidance as needed
- Multi-user functionality, facilitating collaborative learning and team projects by allowing multiple users in the same virtual space
- Integration with learning management systems, seamlessly tracking student progress and assessments
- Haptic feedback, enhancing the realism of the experience by incorporating tactile sensations where possible

Virtual workshops can be particularly valuable in the following contexts:

- High-risk or high-cost training scenarios, such as in fields like aviation, nuclear energy, or advanced manufacturing
- Replicating rare or dangerous situations, such as emergency response training or handling hazardous materials

- Allowing repeated practice to build muscle memory, which is particularly useful for developing procedural skills or refining techniques
- Simulating equipment not physically available, exposing students to a wider range of tools and technologies than a physical workshop could provide
- Scale and perspective shifting, enabling students to explore environments at different scales, from the microscopic to the architectural
- Rapid prototyping and design iteration, speeding up the prototyping process in fields like engineering or product design

It is crucial to emphasize that virtual workshops should complement rather than replace hands-on training with real equipment. A blended approach that combines VR and physical practice is likely to be the most effective for skill development, allowing students to benefit from the advantages of both virtual and real-world learning environments.

6. Implementation recommendations

Based on our analysis and the experiences of early adopters, we offer the following detailed recommendations for institutions looking to implement VR in vocational training programs. We strongly advocate beginning with small-scale pilot projects, which allow institutions to test effectiveness and gather feedback in a single course or module before attempting wider implementation. This approach enables refinement of methodologies and systems before full-scale deployment.

Critical to success is the provision of comprehensive training for instructors, encompassing both technical training on VR systems and pedagogical guidance for effective integration into teaching practices. The establishment of a community of practice can provide valuable ongoing peer support. Additionally, careful alignment with existing curriculum is essential, with VR activities being precisely mapped to established learning objectives and competency frameworks. It is crucial to avoid implementing VR solely for its novelty; each application should serve a clear pedagogical purpose.

Institutions should develop clear guidelines for VR use, establishing specific protocols that delineate when VR is more appropriate than traditional methods. These protocols should take into account various factors including learning objectives, student readiness, and resource availability. The development of industry partnerships is also vital, enabling collaboration with employers to ensure VR simulations accurately reflect current workplace practices and technologies, while potentially offering opportunities for co-development of VR content.

Continuous evaluation and refinement should be fundamental to the implementation process. This requires the establishment of robust assessment mechanisms to measure VR's impact on learning outcomes, with the resulting data being used to iteratively improve integration. Accessibility must be carefully considered, ensuring VR systems are usable by students with different physical abilities and providing alternatives for students who cannot use VR due to health concerns such as motion sickness.

Health and safety considerations should be formalized through specific guidelines covering time limits, ergonomic setup, and hygiene practices for shared equipment. While off-the-shelf VR applications can be valuable, institutions should consider investing in quality content development, potentially creating custom content tailored to specific curriculum needs. Technology lifecycle planning is essential, requiring budgeting for regular updates and replacements of VR hardware and software, given the rapid evolution of technology in this field.

Adequate technical support is crucial, necessitating IT staff trained in VR system troubleshooting and readily available during class times. Integration with other educational technologies should be considered, examining how VR can complement existing tools such as learning management systems, digital textbooks, and online collaboration platforms. Institutions should foster a culture of innovation, encouraging faculty and students to experiment with VR and share experiences, potentially through showcases or competitions for VR projects.

Institutional change preparation is necessary, as VR integration may require adjustments to teaching spaces, schedules, and assessment methods. These changes should be planned proactively. Ethical considerations must be addressed through policies covering data privacy, content appropriateness, and potential psychological impacts of immersive experiences. Finally, scalability should be considered as institutions move beyond pilot projects, examining how VR can be implemented across multiple courses or programs in a cost-effective manner.

7. Challenges and considerations

While VR offers significant potential benefits for vocational training, several challenges and considerations must be carefully evaluated for successful implementation. The high initial costs of VR hardware and software represent a significant barrier, requiring institutions to carefully consider return on investment and explore various funding options. This financial consideration is compounded by the need for ongoing technical support, as VR systems require regular maintenance, updates, and troubleshooting, necessitating dedicated technical staff with specialized knowledge.

Student comfort and wellbeing present another crucial consideration, as some users may experience motion sickness or eye strain with prolonged VR use. Institutions must establish clear protocols to address these issues. Additionally, cognitive overload can occur if VR environments are too complex or poorly designed, potentially overwhelming students rather than enhancing learning. This underscores the importance of careful instructional design in VR implementation.

The assessment of skills transfer poses a significant challenge, as it can be difficult to accurately measure how well skills learned in VR translate to real-world settings. This necessitates the development of robust assessment methods. Furthermore, institutions must strike a careful balance between virtual and hands-on practice, as there is a risk of overreliance on VR at the expense of crucial hands-on experience with real equipment.

The rapid pace of technological change in VR development means systems may become outdated quickly, requiring regular upgrades. This technical challenge is often accompanied by human factors, as some faculty may be resistant to incorporating VR into their teaching, highlighting the importance of change management and professional development programs.

Equity and access present ongoing challenges, as institutions must ensure all students have equal access to VR technology, both in and out of the classroom. Content development represents another significant hurdle, as creating high-quality, educationally effective VR content can be both time-consuming and expensive. Integration challenges also exist, as VR systems need to work seamlessly with other educational technologies and processes already in place.

Ethical considerations require careful attention, particularly regarding data privacy, content appropriateness, and psychological impact. Additionally, regulatory compliance must be addressed, as training methods in some fields need to meet specific regulatory requirements, which VR systems must satisfy.

These challenges and considerations should be carefully weighed against potential benefits when considering VR implementation. A thorough needs assessment and strategic planning process can help institutions effectively navigate these challenges while maximizing the educational potential of VR technology.

8. Conclusion

This paper has presented comprehensive methodical foundations for integrating virtual reality into professional training programs in vocational higher education. The proposed model and pedagogical conditions provide a structured framework for systematic VR implementation that aligns with curriculum goals and pedagogical best practices.

Virtual workshops and laboratories offer particularly promising applications for enhancing practical skills development in vocational education. By providing safe, repeatable, and customizable learning experiences, VR can significantly enhance the depth and breadth of training provided to students.

However, it is crucial to emphasize that VR should be viewed as a complement to, rather than replacement for, traditional hands-on training methods. A blended approach that combines the strengths of both virtual and physical learning environments is likely to yield the best results in terms of skill development and knowledge retention.

References

[1] S. H. Lytvynova, S. O. Semerikov, A. M. Striuk, M. I. Striuk, L. S. Kolgatina, V. Y. Velychko, I. S. Mintii, O. O. Kalinichenko, S. M. Tukalo, AREdu 2021 - Immersive technology today, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 1–40. URL: https://ceur-ws.org/Vol-2898/paper00.pdf.

[2] R. R. Ravichandran, J. Mahapatra, Virtual Reality in Vocational Education and Training: Challenges and Possibilities, Journal of Digital Learning and Education 3 (2023) 25–31. doi:10.52562/jdle.v3i1.602.

[3] Amin, I. Widiaty, C. Yulia, A. G. Abdullah, The Application of Virtual Reality (VR) in Vocational Education, in: Proceedings of the 4th International Conference on Innovation in Engineering and Vocational Education (ICIEVE 2021), Atlantis Press, 2022, pp. 112–120. doi:10.2991/assehr.k.220305.024.

[4] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, Development of digital competencies in immersive cloud-based educational environment, CEUR Workshop Proceedings 3781 (2024) 203–208. URL: https://ceur-ws.org/Vol-3781/paper27.pdf.

[5] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, V. N. Soloviev, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, D. S. Shepiliev, Immersive E-Learning Resources: Design Methods, in: Digital Humanities Workshop, DHW 2021, Association for Computing Machinery, New York, NY, USA, 2022, p. 37–47. doi:10.1145/3526242.3526264.

[6] C. Udeozor, R. Toyoda, F. R. Abegão, J. Glassey, Perceptions of the use of virtual reality games for chemical engineering education and professional training, Higher Education Pedagogies 6 (2021) 175–194. doi:10.1080/23752696.2021.1951615.

[7] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, Immersive cloud-based educational environment of the university: Design principles, CEUR Workshop Proceedings 3771 (2024) 126–135. URL: https://ceur-ws.org/Vol-3771/paper27.pdf.

[8] T. H. Kramarenko, O. S. Kochina, The use of immersive technologies in teaching mathematics to vocational students, Journal of Physics: Conference Series 2611 (2023) 012006. doi:10.1088/1742-6596/2611/1/012006.

[9] L. Mekacher, Augmented reality (AR) and virtual reality (VR): The future of interactive vocational education and training for people with handicap, PUPIL: International Journal of Teaching, Education and Learning 3 (2019) 118–129. doi:10.20319/pijtel.2019.31.118129.

[10] J. Spilski, C. Giehl, S. Schlittmeier, T. Lachmann, J.-P. Exner, A. Makhkamova, D. Werth, M. Pietschmann, Potential of VR in the Vocational Education and Training of Craftsmen, in: Proc. 19th International Conference on Construction Applications of Virtual Reality (CONVR), Bangkok, Thailand, 2019, 2019. URL: https://www.researchgate.net/publication/337339626.

[11] S. L. Kucher, R. M. Horbatiuk, M. M. Ozhha, N. M. Hryniaieva, Use of information and communication technologies in the organization of blended learning of future vocational education professionals, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 54–66. URL: https://ceur-ws.org/Vol-3679/paper39.pdf.

[12] J. Man, F. Guo, C. Ma, Innovative Analysis of Higher Vocational Education Model Based on Virtual Reality Technology, Journal of Physics: Conference Series 1533 (2020) 022097. doi:10.1088/1742-6596/1533/2/022097.

[13] O. O. Lavrentieva, I. O. Arkhypov, O. P. Krupski, D. O. Velykodnyi, S. V. Filatov, Methodology of

using mobile apps with augmented reality in students' vocational preparation process for transport industry, in: O. Y. Burov, A. E. Kiv (Eds.), Proceedings of the 3rd International Workshop on Augmented Reality in Education, Kryvyi Rih, Ukraine, May 13, 2020, volume 2731 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 143–162. URL: https://ceur-ws.org/Vol-2731/paper07.pdf.

[14] L. Fadieieva, S. Semerikov, Exploring the Interplay of Moodle Tools and Student Learning Outcomes: A Composite-Based Structural Equation Modelling Approach, in: E. Faure, Y. Tryus, T. Vartiainen, O. Danchenko, M. Bondarenko, C. Bazilo, G. Zaspa (Eds.), Information Technology for Education, Science, and Technics, volume 222 of *Lecture Notes on Data Engineering and Communications Technologies*, Springer Nature Switzerland, Cham, 2024, pp. 418–435. doi:10.1007/978-3-031-71804-5_28.

[15] P. Nechypurenko, T. Selivanova, M. Chernova, Using the Cloud-Oriented Virtual Chemical Laboratory VLab in Teaching the Solution of Experimental Problems in Chemistry of 9th Grade Students, in: V. Ermolayev, F. Mallet, V. Yakovyna, V. S. Kharchenko, V. Kobets, A. Kornilowicz, H. Kravtsov, M. S. Nikitchenko, S. Semerikov, A. Spivakovsky (Eds.), Proceedings of the 15th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kherson, Ukraine, June 12-15, 2019, volume 2393 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2019, pp. 968–983. URL: https://ceur-ws.org/Vol-2393/paper_329.pdf.

[16] P. Nechypurenko, O. Evangelist, T. Selivanova, Y. O. Modlo, Virtual Chemical Laboratories as a Tools of Supporting the Learning Research Activity of Students in Chemistry While Studying the Topic "Solutions", in: O. Sokolov, G. Zholtkevych, V. Yakovyna, Y. Tarasich, V. Kharchenko, V. Kobets, O. Burov, S. Semerikov, H. Kravtsov (Eds.), Proceedings of the 16th International Conference on ICT in Education, Research and Industrial Applications. Integration, Harmonization and Knowledge Transfer. Volume II: Workshops, Kharkiv, Ukraine, October 06-10, 2020, volume 2732 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 984–995. URL: https://ceur-ws.org/Vol-2732/20200984.pdf.

[17] S. O. Semerikov, M. M. Mintii, I. S. Mintii, Review of the course "Development of Virtual and Augmented Reality Software" for STEM teachers: implementation results and improvement potentials, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 159–177. URL: https://ceur-ws.org/Vol-2898/paper09.pdf.

[18] O. Tsvetkova, O. Piatykop, A. Dzherenova, O. Pronina, T. A. Vakaliuk, I. Fedosova, Development and implementation of virtual physics laboratory simulations for enhanced learning experience in higher education, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 98–110. URL: https://ceur-ws.org/Vol-3679/paper10.pdf.